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THE STUDY OF FUEL OIL PUMPABILITY USING A LABORATORY PUMPING RIG

ADMIRALTY OIL LABORATORY,
BRENTFORD, MIDDLESEX

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by

D. Wyllie and J. T. Jones

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

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A.O.L. Report No. 33

October 1962

Admiralty Oil Laboratory, Brentford

The Study of Fuel Oil Pumpability using a Laboratory Pumping Rig

by D. Wyllie and J. T. Jones

Introduction

Previous reports in this series have described the condition of Admiralty furnace fuel oils in long-term shore storage,(1)(2)(3)(4) pumping trials conducted in depot pipe lines(5)(1)(2)(3) and limited trials in ships(6). Considerable difficulties were experienced in organising sea trials as the very few ships which could be allocated for the purpose all had other commitments of higher priority and the information obtained was therefore very limited. The large scale pumping trials in depots, on the other hand, were sufficiently comprehensive and a good deal of information became available as a result. These trials, however, inevitably suffer from the disadvantage that the temperature of the fuel cannot be adjusted to any required level before the trial and the pipelines during the trial are exposed to the prevailing air temperatures. In addition, the pipes may have been in use for some years and their internal condition can only be imagined. It was decided that a rig should be constructed which would be large enough to reproduce the actual conditions which might exist in a small ship, yet be small enough for the essential parts to be housed in a cold room. The problems which can usefully be studied in such a rig are:-

(a) the clearing of a line of gelled oil,

(b) the pumping rates achievable with fuels of differing types at temperatures which might occur ashore or on board ship,

(c) the rate of breakdown of a gelled or near gelled fuel when it is pumped along a pipe,

(d) the relation between apparent yield value, rate of flow and apparent viscosity in the pipe and yield value and apparent viscosity measurements in laboratory apparatus.

In such a rig, it should be possible to conduct repeated line clearing experiments, to work at any temperature in the required range and, by a suitable choice of pipe length and diameter, to obtain the required range of shear stresses and rates of shear. It should also be possible to set up the rig in such a manner that any marked breakdown of "structure" and apparent viscosity of the fuel, as it passed down the pipe, would be detected and not masked by the imperfection of the pipe system, the possibility of air-locks and the difficulties of measurements in the field.

The original proposal to construct a laboratory pumping rig was made by the Admiralty Fuels and Lubricants Advisory Committee, in 1952, and A.F.L.A.C. Panel B was formed to consider this suggestion. However, for a variety of reasons, only slow progress was made until after large scale pumping trials in the Killingholme and Lyness Oil Fuel Depots in the winter months of 1953 to 1956. The rig was then built in the light of experience gained in the large scale trials. A.F.L.A.C. Panel B at this stage merged with A.F.L.A.C. Panel F, which had been concerned in all other aspects of fuel oil pumpability, including the large scale trials.

The laboratory pumping rig was constructed and has been operated by the staff of A.O.L. although, because of the space required, the actual rig is sited at A.E.L., West Drayton. Its construction and initial proving trials, together with the early history of the project have been described in A.O.L.

Technical Note No. 16 of July 1958(7). The rig was used for the next two and a half years to study the behaviour of six typical fuels under the most adverse conditoons which, it was considered, might exist in a damaged ship in Arctic waters. The results obtained in the rig itself have, throughout, been compared with rheological measurements in co-axial cylinder viscometers and yield value tubes of various types. The results obtained in the first half of the programme were presented as part of the Institute of Petroleum Symposium on the Flow Properties of Admiralty Furnace Fuel Oils in January 1960 and were subsequently published in the Journal of the Institute of Petroleum(8). The emphasis was then placed on the scientific aspect of the work rather than on its application to ship problems. It is proposed, in this report, to present the results of the completed programme and to pay more attention to specific ship problems than would be permissible in a published paper.

2. Description of Rig

An instrumented length of 4 inch internal diameter pipe was connected to the suction side of a pump, the instrumented length being contained inside a temperature controlled room. Six storage tanks were provided outside this room and one inside; all tanks could be connected to the suction side of the pump, either directly or through the instrumented length, or to the discharge side of the pump. Provision was made for measuring temperatures, pressures and flow rates, all indicating instruments being concentrated at one spot outside the room for easy use during runs. The layout of the rig is shown schematically in Fig. 1 and as a scale drawing in Fig. 2. Fig. 3 shows the coil and the original inside tank during construction.

The pipe systems were made from 4 inch internal diameter, hot finished, steel pipe and all isolating valves were gate valves. The instrumented length was 133 ft. long and was fitted as a rectangular coil of constant rise with all bends of at least 1 ft. radius to reduce bend effects. The internal storage tank, holding approximately 450 gallons, was situated in the centre of the coil and was connected to the coil at the bottom. Each end of the 133 ft. length was fitted with a vertical branch, holding a transparent glass tube which rose to a height of about 4 ft. from the lower part of the coil. Air-vents and drain-cocks were situated in convenient positions.

The six external storage tanks were of 500 gallon capacity and were fitted with dip rods calibrated to read in 1 gallon intervals. Each tank contained a steam coil for heating; each also had suction and drain connections at the bottom; and, at the top, a filling connection and a connection from the discharge side of the pump. One tank, No. 2, was fitted with one additional pump discharge connection at a lower level, to enable oil to be discharged below the oil level, when required, to prevent the entrainment of air.

A 4"/5", motor driven, Drysdale Vertoil pump was used and this was driven by a D.C. motor, limited speed control being available by means of a variable resistance in the field circuit. The pump was of the gear wheel type and was considered to be typical of those used in service for transferring fuel oil. Initially, a flow-meter was situated on the discharge side of the pump: this was a Brodie-Kent X77 positive displacement meter of the semi-rotary piston type. This flow-meter had been used on previous large scale trials and was known to give the required accuracy. The quantity of oil passing the flow-meter was indicated on a direct reading counter graduated in tenths of a gallon. With this arrangement the flow rate through the coil could be controlled by varying the speed of the pump. For the lower flow rates, a Comet $1\frac{1}{4}$ inch positive displacement pump was installed, parallel to the larger pump. This pump contained spring loaded vanes, running in an eccentric housing. At a later date, it was desired to operate the rig by maintaining a constant pressure drop across the coil. This could only be done by permitting the pump to take its suction directly from an outside tank, at the same time as from the coil, and by varying the quantity of oil reaching the pump from the outside tank. It was therefore necessary to re-position the flow-meter adjacent to the coil, i.e. on the suction side of the pump before the direct connection to the outside tanks. With this modified layout, the larger pump was found to give the necessary control and the smaller pump was no longer used.

The 133 ft. length of the coil was fitted with transducers for indicating pressures at six points, as evenly spaced along its length as practicable.

Branch connections were made at each point, so that the transducer heads were in line with the inside wall of the pipe and did not obstruct the flow. The transducers were Salford Electric Company instruments and the pressures were indicated on distant reading galvanometers mounted on a panel outside the temperature controlled room. Each transducer was calibrated to read pressures from +5 to -15 p.s.i. to an accuracy of ± 1% of the full scale reading (± 0.2 p.s.i.). These instruments had also been used previously at full scale pumping trials, when it had been found that an accuracy better than this was usually obtained.

All temperatures were measured by copper-constantan thermocouples connected to 12-point Honeywell Brown potentiometric recorders stamping every 30 seconds. Each 500 gallon storage tank and the 450 gallon internal tank was provided with seven thermocouples and thermocouples were also provided at the inlet and outlet of the coil and pump. Additional thermocouples were supplied at different points in the room, in the wall of the pipe at point No. 6 and for use with the laboratory instruments, such as Ferranti and conicylindrical viscometers and C.R.C. tubes, also situated in the room. As temperature measurements were not required from all the external tanks at any one time, the points in the recorders were distributed to read the temperatures required for the particular experiment.

It was also required to measure temperatures across the pipe in some of the experiments. Three points were selected; one between transducers Nos. 1 and 2, one between transducers Nos. 3 and 4 and one near transducer No. 6. Three thermocouples were fitted at each point, evenly disposed horizontally across the pipe at the first two points and vertically at point No. 6. These were connected to two further recorders, with 5 second interval stamping, and positioned to give a continuous picture of the temperature distribution across the pipe at these points.

The temperature controlled room was a standard Lightfoot 40 ton food store, modified by A.O.L. to give much better temperature control than its original design permitted. The cooling system was in three parts. Firstly, a refrigerator unit, employing Arcton 6 as the refrigerant, cooled brine in the brine tank; secondly, the brine was circulated around coils in a compartment of the room; and thirdly, two 12 inch fans circulated air over the brine coils and through the main part of the room, on a closed cycle. A resistance wire heating element, supplied with current through a Variac, was situated on the air inlet side of the fans and provided the necessary heat for the higher temperatures.

The refrigerator unit was controlled by a coarse thermostat in the brine tank which could be set by hand. The temperature of the brine pumped through the brine coils was regulated by permitting varying quantities of brine to re-pass through the coil without passing through the brine tank; this was performed by an automatic by-pass valve operated through an electronic panel and controlled by two sensitive thermostats in the main part of the room. The set point (i.e. the temperature required in the room) was regulated by setting a potentiometer fitted on the panel. This potentiometer was operated by an oscillating follower on a cam, which was of the form of an Archimedean spiral and could be set in one position, or rotated to reduce the set point by 1°F per day between 60°F and 32°F.

It may be noted in Figure 2 that the "Rig", as designed and constructed, also included two 33 ft. coils of one inch internal diameter pipe, with sight glasses at the ends, as with the 4 inch pipe coil, which could be included in or isolated from the larger coil by appropriate valves, as desired. These coils were intended to permit "scale effects" to be studied and provided an intermediate scale between glass laboratory apparatus and the 4 inch pipe. The length/diameter ratio of the smaller coils was the same as that of the larger. In fact, the smaller coils were never used.

The electricity for all the instruments used was supplied through a voltage stabiliser.

3. Fuels Studied

It was considered that about six fuels, each one of the more viscous examples of its type, would be sufficient to provide information of the worst state which might reasonably be expected from fuels purchased to R.N. specifications under adverse conditions (e.g. in a damaged ship in Arctic waters). While it would be of interest to study a larger number of fuels, six were as many as could be examined in a reasonable time. Any others which may be of special interest can, if the need arises, be studied later. The fuels chosen were of different types, selected on grounds of general experience; partly, as a result of the actual condition of fuels examined in shore storage, or pumped under observed conditions in depot pipelines; and, partly, to include "borderline" fuels, about the limit or just outside the pumpability requirements laid down in specifications E. in C. 0-1 and 0-1A for Schedule 390 and 390A fuels. The relevant details of R.N. furnace fuel oil specifications from 1939 to 1962 are set out in Table 1 and particulars of the fuels selected for study are set out in Table 2.

(a) <u>Persian F-36 ex Tank 7 Killingholme</u>

Considerable quantities of Persian F-36 fuels were supplied prior to the temporary closing of Abadan refinery, owing to political troubles, in 1951. Flow points were normally 45 or 50°F and viscosities at 122°F about 100 secs. Redwood I, i.e. about the maximum permissible for fuels of this flow point. Some supplies, such as this tank, were a little above the 100 second limit. These fuels were normally fluid and easily handled at temperatures much above 50°F, but thickened rapidly as the temperature was reduced. At the time of the winter pumping trials, at the Killingholme depot in February 1955, this fuel had gelled at the surface, but the bulk oil beneath the gelled layer was pumped without undue difficulty at 50°F. The performance of this oil at 32 to 36°F was considered likely to be of interest.

(b) <u>Persian F-21 ex Tank 38 Killingholme</u>

This fuel is well outside the pumpability requirements of any R.N. specification published since 1953. Considerable quantities of Persian F-21 fuel were purchased between 1948 and 1951. The fuel in Tank 38 Killingholme gelled very firmly on top during winter months. In February 1955, when it was pumped, fluid but viscous oil came into the pipeline at 52°F and moved so slowly that, with air temperatures around 30°F, it cooled and was only with difficulty got out of the pipe before it gelled. This fuel was clearly an extreme case and it was decided to examine it in the rig last of all.

(c) <u>Bahrein ex Tank 40 Invergordon</u>

This fuel was part of a consignment supplied against U.S.N. specification MIL-F-859 for U.S. Navy Special fuel. But, since none of the consignment met the specification requirement for a pour point of 15°F maximum, it must have been "approved" as passing the P. & O. fluidity test in place of the pour point requirement. This is now permissible under the terms of the latest version of the specification, MIL-F-859D, but at that date it was not. The consignment gelled during the first winter to such an extent that half-bricks placed on top of the oil in the tanks did not sink. The bulk of the oil beneath the gelled layers remained fluid but of high viscosity at temperatures of 50 to 55°F. After three years storage, the fuel was issued in autumn to Fleet tankers and, as a high loading rate was demanded, the tanks had to be heated. A.O.L. became specially interested in this oil when it was discovered that the oil in Tank 40 met the flow point-viscosity requirements laid down in R.N. specifications. Other tanks examined were more viscous than this, but at least one other complied with the R.N. requirements.

(d) <u>Curacao ex Tank 50 Killingholme</u>

Schedule 390 fuels, now known as Grade 75/50, may have viscosities at 122°F of up to 300 secs. Redwood I, if flow points do not exceed 30°F. Fuels purchased against this requirement are normally supplied to the R.N. from Trinidad, Aruba or Curacao. Trinidad and Aruba fuels have been found to have flow points of 0°F, or less, and in bulk storage have cooled to 30 to 40°F whilst still remaining fluid and not unduly viscous. This Curacao fuel, however, although its flow point was -10°F, was found to have thickened in storage when its bulk temperature was only 47°F during the winter pumping trials in February 1955. Low flow point Aruba fuel in the depot at that time had a temperature of 36°F. The Curacao fuel was therefore selected for rig trials. As few of the considerable number of fuels from this refinery were available for inspection in U.K. long term storage, it is not known whether its storage behaviour is good, poor or average for oil from this source. It would, however, appear possible that similar fuels with viscosities of 300 secs. Redwood I at 122°F might have storage properties inferior to those of this example.

(e) Kent ex Tank 8 Killingholme

A number of fuels produced by Kent Refinery from Middle East Crude have been studied in depots. This one was the most viscous in shore storage; this is not surprising as it was found after delivery that it failed to meet the flow point-viscosity clauses for Schedule 390 and 390A fuels. If, however, its flow point had been 40°F, not 45°F, it would have been acceptable. This is the only one of a number of consignments having viscosities at 122°F between 150 and 175 secs. Redwood I which had a flow point greater than 40°F. All others had flow points of 25 to 40°F and were acceptable. It was selected for rig trials as an unusual and the least pumpable speciment received from the Kent Refinery.

(f) Mixed Kent and Stanlow ex Cell 5 Rosyth

Fuel from this cell was taken for Arctic pumping trials in R.F.A. Tidereach in January 1959, described in another report(6). The oil had shown signs of thickening in the cell between January 1959 and a previous inspection in March 1958. It was found that the oil taken on board R.F.A. Tidereach remained very fluid down to 44°F, the lowest temperature to which it cooled in the time available for the trial. Meantime, arrangements had been made for the small amount of oil remaining in Cell 5 to be despatched to A.E.L. for trial in the rig. This residue proved to be thicker than any samples taken from the cell and much thicker than the fuel received on board. Moreover, it failed the pumpability clauses of R.N. specifications. It is considered that some segregation must have taken place in store and that this residue was less pumpable than the bulk oil supplied. However, it provided another extreme example for rig trials.

These six fuels were transported to the rig in 40 gallon drums. The F-36, F-21 and Curacao fuels were stored in the 500 gallon storage tanks provided. The others were put into convenient drum storage in the vicinity until required.

4. Basis for Operation of the Pumpability Rig

An installation of the type described in Section 2 of this report could have been regarded merely as a means of simulating typical service conditions, such as time of cooling before pumping and applied shear stress, in order to ascertain whether selected fuels could be pumped under the conditions postulated. In addition, however, it was desired to learn more of the relationship between practical pumping and measurements made in laboratory apparatus.

The items on which information was required were reduced to three:-

(a) the minimum shear stress required to produce flow;

(b) the time required to achieve a steady rate of flow; and

(c) the steady flow rate which could be achieved with the forces available.

The large scale field trials(4)(9)(10) gave the following information:-

(a) flow could be expected once the yield value of the oil, as determined in laboratory yield value tubes, had been exceeded; (To this was added the rider that flow could even commence after many hours pumping when the average shear stress along the line initially gelled was less than the yield value determined in small yield value tubes).

(b) the rate of increase in flow could be deduced by direct comparison with the increase of shear rate when the oil was subjected to a constant shear stress in a coaxial cylinder viscometer.

(c) pipe viscosities, once steady flow conditions had been established, were normally about the same magnitude and probably never more than twice equilibrium viscosities determined in coaxial cylinder viscometers at the same rate of shear.

Let us examine, more closely, the factors involved:- Bingham[11] showed that a gelled fluid in a pipe commences to flow when the shear stress at the pipe wall exceeds the yield value. This was elaborated by Buckingham[12] into an equation to describe the flow of the fluid as the plug moves along the line and slowly breaks down. His treatment, however, assumed that the fluid has a unique viscosity for each applied stress, not a viscosity which changes with time of shearing. At the time the Panel's work commenced, little useful information was available as to the properties of time-dependent fluids.

It is known that visible flow does not commence, immediately stress is applied to a gelled fuel, unless the stress is well above its yield value. It has been suggested that the delay is caused by the high initial viscosity of the fuels and the time required for the movement to reach measureable dimensions. This has led to discussion as to how much movement in a four inch (or larger) pipe shall be regarded as equivalent to the initial movement detectable in a narrow ($1\frac{1}{2}$ cm) yield value tube. So far, the possible distortion of the gel before yielding has not been considered at all. Billington's[13][14][15][16] treatment of the gelled fluid as visco-elastic, involved the assumption that the gel will distort in response to any applied stress until the strain equals the stress or the elastic limit is passed and flow commences. This envisages movement under stress before the point is reached at which flow commences.

The $1\frac{1}{2}$ mm diameter yield value tube, originally described by Gill and Russell[17] and employed by the A.F.L.A.C. Panel[18], was the principal apparatus employed to determine yield value. A few results were obtained in the 1 cm diameter tubes described by workers at the U.S. Naval Boiler and Turbine Laboratory and developed from those originally described by the California Research Station. These tubes are referred to herein as C.R.C. tubes[19][20]. They have been claimed to be less liable to error, owing to the possible presence of air bubbles, than are the narrow bore yield value tubes.

Voids and air bubbles can also occur in a large pipe, especially if the oil is cooled in a pipe which is sealed at both ends. The stand pipes were used as a reserve of oil to permit the pipe to be cooled with the valves at each end shut. When the oil gels, it is still subject to strain caused by expansion and contraction with fluctuation in the temperature of the cold room, even although these may not exceed ± 1°F.

Both the A.F.L.A.C. Panel's yield value method[18] and the C.R.C. method [20] apply shear stress increasing in steps by about 30 dynes/cm^2 every five minutes. The Panel's method takes yield value as the shear stress at which first movement is observed. This may be high, because insufficient time is permitted for visible movement to take place, whether we ascribe this delay to purely viscous effects or to visco-elastic effects. An alternative procedure, therefore, is to subject a series of tubes to a series of shear stresses, one shear stress per tube, and note the time that elapses till movement occurs.

In practice, it is required to know the shear stress at which flow in a pipe will commence in a "reasonable time", which obviously must be defined for the purpose in hand. It was considered that ships' staff would not take kindly to a situation in which no measurable flow occurred in 30 minutes, or at most one hour, after starting up.

It had originally been intended to conduct the yield value experiments via the stand tubes, then switch to the main pump once some movement of oil had already occurred. It was decided after preliminary trials not to attempt to determine minimum yield value in the four inch pipe, since on the one hand this would entail increasing the shear stress applied to the pipe by small increments at intervals of one hour or more and would be very time consuming, and on the other hand would upset the time scale for the subsequent pumping of the line. Instead, each run was conducted by putting a suction on the line, using the main pump and operating it and the valve system to give some definite pressure drop down the line. The flow, obtainable on start up, and the rate of shear of breakdown were to be compared with the results obtained in constant shear stress coaxial cylinder viscometers.

Experiments were carried out under two conditions. First, with a gelled line and tank full of gelled oil, i.e. both line and cold room tank filled and cooled until both had ample time to stabilise at cold room temperature. On pumping, the oil initially in the pipe was continually replaced by cold oil from the tank. The second condition was that in which the line was cold and gelled, the cold room tank containing warmer fluid oil. This condition could occur in a depot if the lines were left full of oil in the winter; or, in a ship, when the pipe passes through flooded compartments. Under this condition, as the cold gelled oil passes through the pipe, it is replaced by fluid oil of much lower viscosity. Even if the total pressure drop from cold room tank to pump is held constant, this pressure is largely confined to a shorter and shorter length of cold gelled oil. The shear stress on this cold oil thus rises and the oil ultimately leaves the line rapidly.

It was decided to attempt to simulate both conditions in the programme. A further step was to fit groups of three thermocouples across the pipe at three points and connect these to high speed recorders to establish, in the line clearing experiments, when the warm oil displaced the cold oil and whether it did so on an even front.

Once steady flow was established, the field trials indicated that the pipe viscosity may be expected to be the same as, or at most twice, the laboratory equilibrium viscosities at the same rate of shear. The rate of shear was selected by applying Poiscuille's equation to the flow, i.e. no account was taken of the non-Newtonian characteristics of the oil. This is an empirical rule based on field experiments. It was also found, in the field, that the disturbing effect of drawing the oil from the tank into the pipe and accelerating it, from rest to the rate of flow in the pipe, must have done a substantial amount of shearing. It was observed that pressure drops, and therefore shear stresses in the first section of the pipe, were sometimes greater than those further along. But within the possible error, normally about 25%, it was not possible to detect any further decrease of shear stress as the oil passed down the pipe.

It was considered that direct observation of pressure drops along the 4 inch pipe would confirm the presence or otherwise of substantial breakdown as the oil moves down the pipe. In order to perform viscosity measurements at constant rates of shear, steel beakers of about the same diameter as the pipe were filled, each time the pipe was filled, and left in the cold room. In addition, steel beakers were hung in the cold room tank at various levels to retain oil from these levels when the tank was pumped out. Several Ferranti Portable Viscometers were employed on these samples. These viscometers were not left continuously in the cold room, but were placed gently in position in the samples to be tested on the day before they were operated.

5. Preliminary Proving Runs

(a) Calibration

In order to gain experience with the control of the rig, to ascertain the actual pipe diameter and the possible errors of the various instruments, proving runs were carried out at 32 to 67°F, using a calibration oil which behaved as a Newtonian fluid at temperatures in this range. From these runs it was determined that:-

(i) the true internal diameter of the test coil installed in the cold room was 3.96" (± 0.04) and the nominal internal diameter of 4 inches could therefore be used in calculations;

(ii) the pressure transducers, which were stated to have an accuracy of ± 0.3 p.s.i., if frequently calibrated would give pressure differences which were accurate to ± 0.2 p.s.i. between two points on the coil.

N.B. The results had to be considered in relation to the following:

Average Shear Stress over Pipe	Pressure Drop between pts. 1 and 6 i.e. over whole length
150 dynes/cm^2	3.4 p.s.i.
300 "	6.8 p.s.i.
500 "	11.5 p.s.i.

A pressure difference of 0.2 p.s.i. over sections of the pipe was equivalent to a shear stress of

Points	1 to 6	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	4 to 6
Shear Stress dynes/cm^2	9	50	40	45	37	57	22

(iii) rates of flow could be read to an accuracy of ± 1% and a flow of 0.02 gallon could be detected at low flow rates;

(iv) temperatures could be read to about ± 0.5°F with the Honeywell Brown recorders

(v) the temperature variation over the whole cold room was about ± 1°F of the required temperature.

Incidentally, it was observed that the centre of the cold room tank cooled much more slowly than the pipe; in order to improve heat transfer and thus save time to reach equilibrium, metal sheets were hung at intervals in the cold room tank during later runs.

(b) Oil Change-over Procedure

After the calibration runs had been completed, the problem to be solved was how to remove the calibration oil from the system, completely, and to replace it by the first test oil. The problem was complicated by the fact that outside ambient temperatures were low and the hut, containing the pumps and pipework, as well as the cold room, was practically unheated, so the temperature of all parts of the system tended to fall rapidly into the range where the calibration oil became very viscous.

It was stored in tank 6, fitted with steam-heating coils, so as much of the oil as possible was pumped back into the tank, heated to 100°F and then pumped around the circuit until the temperatures everywhere approached this temperature. The temperature of the cold room itself was set as high as possible, around 80°F, and the process of removal started by pumping as much oil as possible back into tank 6, removing as much as possible from the cold room tank by portable pump and, finally, opening all drain-cocks and draining for three days. Even then, it was still necessary to clean out the cold room tank and the lowest part of the pump by hand, to ensure that as little as possible of the calibration oil remained.

It will be appreciated that only limited quantities of the test oils could be stored adjacent to the rig, so the minimum wastage by flushing was essential and it was decided to rely on the above draining and cleaning procedure for the tank and pipework inside the cold room, maintained around 80°F, and to use the test oil only for flushing the cold parts of the system outside it, using the minimum quantity considered adequate, and ultimately discharging the "mixed" flushing oil to tank 5, which was used as the slop-tank. Finally, the system was again drained and the lowest parts of the pump cleaned out by hand before the whole rig was filled with the first test oil. This type of changeover procedure was followed each time the rig was filled with a new test oil.

(c) Persian F-36 ex Tank 7 Killingholme

This was the first test oil used. It had been stored in external tanks 1 and 2 for some months before it was tested and had, of course, undergone variations in temperature even more marked than oil in depot storage. The whole rig was filled with this oil, as were the cold room tank and various instruments. The cold room was then set to cool to 36°F. After 14 days, when the oil was pumped out, the pipe had reached 36°F, but the bulk of the oil in the cold room tank had a temperature of about 38°F. For the next run, the oil was allowed 21 days to attain a test temperature of 38°F and was then pumped, after some preliminary work with yield value tubes, both pipe and tank being about the same temperature.

In these two runs (Nos. 42 and 43) the suction rose rapidly to the maximum available and became concentrated along the line of cold oil in the cold room, giving a shear stress between points 1 to 6 of nearly 600 dynes/cm^2 when flow commenced. Once flow commenced and cold oil flowed as far as the pump, the available pressure drop was divided more evenly down the whole line. When steady flow rate had been established the shear stress between points 1 and 6 was between 420 and 460 dynes/cm^2, the exact figure depending on the head of oil in the cold room tank, the pump exerting maximum suction all the time.

Further runs were made after the flow-meter was transferred from the delivery to the suction side of the pump, being now sited as shown in Figs. 1 and 2. It was then possible to hold a pressure drop equivalent to an average shear stress of 400 dynes/cm^2 between points 1 and 6, for the duration of a pumping run. Run 45 was conducted to confirm this, oil which had been in the cold room for some months while the rig was not in use being used for this purpose.

6. Outline of Main Programme

(a) Selection of Test Conditions

When the rig was first proposed, it had been considered that fuels were likely to cool to 32°F in unheated ships' tanks in Arctic waters. The ship trials, which had been attempted meantime, had demonstrated that a more realistic minimum temperature would be 36°F, as the lowest temperature reported in ships' storage tanks were around 36°F. It was, however, still envisaged that fuel lines in a damaged ship might be surrounded by near freezing sea water. It was therefore decided to adopt 36°F as the main temperature in the rig programme and to supplement this with line clearing experiments in which the pipe had been filled with fuel and cooled to 32°F.

These experiments at 36°F and 32°F were aimed entirely at conditions in unheated or damaged ships. In addition, it was decided to study the oils at 48°F, which is the lowest temperature likely to occur in underground storage, where oil cannot safely be heated, and therefore an important temperature in relation to any new specification pumpability test for the R.N.

The next important point to be decided was the time fuel should be allowed to attain the test temperature before its condition was assessed by pumping or other means. Fuel in shore storage may be left undisturbed for years; fuel in unheated ships' tanks may be in Arctic waters for a few weeks before it is required for use. In a damaged ship, in which flooding has occurred and tanks and lines which are required to keep the ship going are surrounded by water, it is unlikely that more than a day or two will elapse before an attempt is made to pump fuel.

Although it might be theoretically desirable to study the condition of fuel after it had stood undisturbed at 48°F for an extended period, it would not be justifiable to use the rig in this manner. The aim rather was to leave it undisturbed long enough to permit the oil to obtain a reasonably uniform condition. This condition need not necessarily be the most viscous it would attain if left longer, but one which was not likely to change appreciably during the pumping and associated rheological measurements.

A few weeks cooling should simulate the cooling of a typical unheated fuel tank in a ship in Arctic waters. Once fuel round the top, bottom and sides of the cold room tank surrounded by air at 36°F gelled or became too viscous to permit convection currents, the rate of cooling of the fuel inside the tank was greatly reduced. Therefore, in order to promote heat transfer, steel plates were suspended vertically in the tank at intervals of about 18 inches, leaving at least a foot unobstructed at the bottom. Nevertheless, the tank centre still cooled considerably slower than the pipe. It was decided that the oil in the tank should be permitted ample time to attain a structure similar to that of the oil in the pipe and, in general, three weeks' cooling was aimed at when both tank and pipe were brought to the same temperature, whether that temperature was 36°F or 48°F.

In line clearing experiments, it was envisaged that, although the pipe might have been surrounded by cold water for a few days, there would be a supply of warmer more fluid oil at the end of the pipe. It was not considered likely that a tank of fuel, even in a damaged and partially flooded ship, would cool to the pipeline temperatures and itself become unpumpable in a few days. Pumping was therefore normally attempted after only two or at most three days at 32°F. Some line clearing experiments were made at 36°F, normally before an attempt to pump the fuel at 32°F, in order to determine, under rather easier conditions, whether an experiment at 32°F would be feasible with the fuel under examination.

It was appreciated that the oils would be sheared by passage through the pump when the pipe system and cold room tank were filled before each run. In summer, the oil would probably be at a temperature of 60 to 70°F on filling. It was decided that in winter the oils should, if possible, be raised to 55 to 60°F by continual circulation through the pump before charging the system. In addition, on two occasions oil was heated to over 90°F in the tank, using the steam heating coils, before charging the system. Normally, the cold room temperature was between 55 and 60°F at the time of filling, but on a few occasions it was brought to the test temperature before filling. The cold room cooled from about 60°F to 36°F overnight. The pipeline could be expected to attain the test temperature in one to two days, but the oil in the centre of the cold room tank, even after the metal plates were put in, took well over a week to attain the test temperature.

Having conditioned the fuel at the test temperature, a suitable shear stress then had to be selected for pumping. At 48°F, the obvious shear stress was that typical of the longest depot suction lines, which had been taken as a basis for the development of the new specification pumpability test. This is 150 dynes/cm^2. In ships' pipelines higher shear stresses are available. The study of ship conditions already referred to indicated that a reasonable minimum available shear stress under ship conditions would be 300 dynes/cm^2 and this was therefore adopted as standard in work at 32°F and 36°F. Additional shear stresses were tried at all three temperatures, either because it was desired to demonstrate by actual pumping the behaviour of the oil under various conditions, or because difficulty was experienced in handling the fuel under the conditions first tried.

A lengthy study of the behaviour of five oils at 32°F, 36°F and 48°F and of the residue from Cell 5 Rosyth under the conditions achieved when bulk oil from this Cell was pumped in the Arctic on R.F.A. Tidereach was then carried through. This was supported by a full range of laboratory rheological measurements. These measurements had to be limited when the oils were pumped after only two or three days cooling, as only a limited number could be made in the cold room within a few hours of the actual pumping. More measurements could be made after three week's cooling, as it could be assumed by then that the condition of the fuel would not change appreciably in a few days, so more time was available.

Practical experience with the operation of the rig showed that the actual fuel temperature at the time of pumping could differ by up to 1°F from that aimed at. The actual shear stress obtained over the whole pipe during pumping could also differ by amounts up to 30 dynes/cm^2 from that intended.

It was found that steady flow could usually be obtained before the full capacity of the cold room had been pumped and, on a number of occasions, the applied shear stress was changed after steady flow had been reached at the initial shear stress and steady flow was reached once more under the new condition before the tank was empty.

(b) Persian F.36 ex Tank 7 Killingholme - Runs 42 to 54 (Tables 3 and 4)

The three preliminary runs with both line and cold room tank filled with cold oil have already been mentioned. It was decided to start the main programme with a run at 48°F. The oil flowed readily under 145 dynes/cm^2 and, when the shear stress was raised to 300 dynes/cm^2, the cold room tank was emptied in a few minutes (Run 46).

Attention was then concentrated on the 36°F condition, starting with line clearing runs. For these, fresh thermocouples were inserted in the line and some difficulty was experienced in obtaining a vacuum tight seal at the thermocouples near point 6, the end of the observed section nearest the pump. In the first line clearing run (No. 47), when full pump suction was applied, a leak developed at this point which rendered the flow-meter readings useless. The line was therefore cleared and repairs executed for a repeat effort (Run 48). The leak, although much smaller, was still sufficient to upset the flow-meter readings and, although the run was carried through, taking the flow rate from tank dips, the results may have been affected by air in the pipe. Even a small volume of air, at atmospheric pressure, represents a substantial volume at low pressure. In all subsequent runs, regular dips were taken in the outside tank in order to detect any air leaks in the system.

It appeared that, after 7 days at 36°F, one hour was required to clear the line, using maximum available suction. Two further line clearing runs followed, both after only three days cooling. In run 49 the line was cleared in 18 minutes using maximum suction; in Run 50, 58 minutes was required, using about 300 dynes/cm^2 overall shear stress. Both cold room tank and pipe were then filled with oil and allowed 16 days to stabilise at 36°F. The line could still be cleared at about 300 dynes/cm^2, but 75 minutes were required (Run 51). An attempt was then made to clear the line after the pipe, only, had been brought to 32°F (Run 52). After only two days at 32°F, considerable difficulty was experienced in clearing the line, about 140 minutes being required at the same stress to reach a flow rate of only 1/10th gallon per minute; it was considered that, with a few more hours cooling, or only slightly less applied shear stress, the line might not have been cleared.

For the next two runs the same oil was heated to over 90°F, as may occur when fuel is heated before being supplied to a ship, then both tank and pipeline brought to 48°F and 36°F for Runs 53 and 54 respectively. Difficulty was encountered when for Run 53 the time came to pump the oil at 48°F under 150 dynes/cm^2. Air temperatures both outside and inside the hut housing the cold room had fallen so low that the line between the cold room and the pump was at 32°F and the oil in the tanks outside was several degrees colder. This oil was circulated round the lines external to the cold room for some time before suction was applied to the test line. Although some flow took place immediately suction was applied, at a shear stress later found to have been 135 dynes/cm^2, not 150 dynes/cm^2 as intended, flow did not exceed 0.2 g.p.m. in 66 minutes. The applied shear stress was then increased to nearly 200 dynes/cm^2 which cleared the line slowly and a steady flow rate was eventually reached.

Owing to a failure of the thermostat, this oil had been unintentionally given an additional heat treatment cycle during storage for this run and this accident may have contributed to its condition. Run 54 at 36°F took place with air temperatures about 50°F and without any thermostat trouble. The line had been cooling for 23 days; after 145 minutes pumping at a shear stress of about 300 dynes/cm^2, flow was still only 0.3 g.p.m. The shear stress was therefore increased to about 400 dynes/cm^2 till steady flow had been established; the run was then completed at 300 dynes/cm^2.

These runs established that there was a resonable possibility of clearing a line of this oil at 36°F using 300 dynes/cm^2 shear stress, after one week's cooling; after three weeks, difficulty might be experienced. It would not be a reasonable risk to allow a line of this oil to cool to 32°F, even for two days, if only 300 dynes/cm^2 were available to clear it. These runs also supplied data on probable pumping rates. Typical flow curves are shown in Fig. 4.

(c) Bahrein ex Tank 40 Invergordon - Runs 55 to 61 (Table 5)

This oil was first pumped (Run 55) after line and cold room tank had been given three weeks to stabilise at 48°F; later, it was pumped at 36°F (Run 56). Pipe viscosities at 36°F were high, but not as high as the condition the shore storage tank concerned had indicated. It also appeared that the fuel had not reached a uniform condition in the tank. The pipe and cold room tank were therefore given seven weeks to cool and stabilise at 36°F and pumping was again attempted at 300 dynes/cm^2 (Run 57). 70 minutes elapsed before the flow rate reached even 1/10th g.p.m. and pipe viscosities were considerably higher than in the previous run. The remaining four runs were all line clearing runs which established that this oil took longer to become difficult to pump at 36°F or 32°F under 300 dynes/ cm^2 than the F.36.

(d) Residue ex Cell 5 Rosyth - Runs 62 and 63 (Table 6)

Although this was the last oil to be added to the programme, it was decided to test it at this stage because it was thought that the results might be relevant to the sea trial in R.F.A. Tidereach. The first run was intended to simulate the actual rate of cooling of the oil which had occurred on board the tanker in the Arctic cruise. After stabilising at 52°F, the temperature at which the oil was loaded on board the tanker, the cold room was cooled at a steady rate to bring the pipe and, if possible, cold room tank also, down to 44°F in ten days. It was then pumped at the two shear stresses employed in the trial at sea. It was realised that this oil was more viscous than that actually taken on board ship, but it was not expected that it would take nearly 70 minutes to reach a flow rate of 1/10th g.p.m. at a shear stress of 110 dynes/cm^2 and 265 minutes to clear the line.

It was then pumped after three weeks at 36°F to provide an additional comparison of "pipe" and laboratory data before it was taken out of the rig.

(e) Curacao ex Tank 50 Killingholme

After the I.P. Symposium on Pumpability, work was resumed with a study of this fuel; unfortunately, it was found after the changeover that the oil in the cold room had become contaminated. However, there was a reserve stock; about two barrels of uncontaminated oil. This did not provide sufficient oil on which to operate the rig, but there was ample for filling beakers for constant rate of shear viscosity measurements, viscometers for constant shear stress viscosity measurements and yield value tubes. These were therefore filled in the usual manner and left in the cold room, which was then brought down from 60°F to 36°F, as quickly as possible, and left at this temperature for almost three weeks. Viscosity and other measurements were then made in the normal manner.

The apparatus was then cleaned out and re-filled. The cold room was brought down from 60°F to 32°F and, after a week, the measurements were repeated, this time at 32°F. Although no pumping had been possible, it was hoped that an estimate of the pumping characteristics of the fuel could be made from these measurements.

(f) Kent ex Tank 8 Killingholme - Runs 64 to 66 (Table 7)

Since the stock of this oil had been laid aside for test in the rig when the cold room tank was only of 150 gallon capacity, and no more had been available later, it was only possible to half-fill the enlarged cold room tank and to pump at one shear stress on each filling. Three pumping runs were made, one at 36.5°F and two at 32.5°F; all at just under 300 dynes/cm^2. In the first, both pipe and tank were filled; and pumped out after 26 days. In the second, only the pipe was filled. It was pumped out after 14 days at test temperature, plus an initial period when

when the temperature control failed. As no pumping difficulties were encountered, in either of these runs, both pipe and tank were filled for Run 66 and given 21 days at about 32°F before pumping. Although it now took two and a half hours to clear the line, it was still possible to pump this fuel at about 300 dynes/cm^2.

(g) Persian F.21 ex Tank 38 Killingholme - Runs 67 to 70 (Table 8)

The fuel was known to be not only well outside the requirements of current specifications, but also much more viscous at winter temperatures than the others. It was therefore expected to be troublesome to handle at 36°F and the programme was planned accordingly. The available supply was again only sufficient to half-fill the cold room tank.

First of all the line was filled and left for seven days at 36°F, then the cold room tank partially filled with freshly pumped fuel at about 50°F and the maximum available shear stress applied to the line (Run 67). The line was cleared, but over seven hours was required to do so. In a repeat test, after three days at this temperature, the line was cleared in 4 hours (Run 68). For the next run, the line was left full of fuel, for six days at 36°F, then freshly pumped oil was put into the cold room tank and an attempt made to clear the line using a shear stress of 300 dynes/cm^2. The line did not yield in six hours, after which pumping was stopped. The next day the maximum available shear stress of over 500 dynes/cm^2 failed to cause appreciable flow in over six hours. The oil in the cold room tank had by then been cooling for about 24 hours and conditions were therefore more severe than in Run 67 when this tank was filled with freshly sheared oil. The cold room was warmed up slightly overnight by bringing the temperature of the oil in the pipe to between 38 to 40°F; the oil in the cold room tank was by this time at temperatures ranging from 38 to 40°F at the tank wall to 43 to 46°F in the centre. Pumping was again attempted at maximum available shear stress and this time the line was cleared in a little over two hours, the shear stress in the test sections falling from 550 to 390 dynes/cm^2 as the cold oil moved on into the rest of the line between the cold room and the pump.

Finally tank and pipe were refilled and left for four weeks at about 50°F. The line was then cleared at 300 dynes/cm^2 in six and a half hours and a nearly steady, but slow rate of pumping achieved.

7. Conditions in the Pipe

The measurements from which the condition of the oil in the pipe can be deduced, were limited to flow rate, pressure and temperature. In the early stages of pumping this flow rate can exceed the true flow rate in the observed sections, owing to the expansion of air bubbles, originally at atmospheric pressure, as the pressure is reduced, or even owing to air coming out of solution in the oil. It is possible for an air bubble to expand to ten to fifty times its original volume, with the pump operating efficiently.

After the initial proving runs, the flow meter was sited on the suction side of the pump at the point where the test line leaves the cold room, in order to minimise this effect and great care taken to get all air out of the line. Initial surges of 0.3 to 0.7 gallons still occurred in the first few minutes of pumping, even under the best conditions. Sometimes the initial surge was several gallons in amount. Flow rates thereafter represented the flow throughout the line.

The flow rate and shear stress at the pipe wall, over the whole of the instrumented length and in each section during typical runs, are plotted against time in Figs. 5 to 10. In the first three, both the oil in the pipe and the oil in the cold room tank were at the same temperature and had been at that temperature long enough to attain approximately the same rheological condition. The second three are line clearing runs with warmer, much more fluid, oil from the cold room tank displacing the oil in the pipe.

Fig. 5 relates to Run 55, the pumping of the Bahrein fuel at 47.5°F after 21 days in the cold room. Steady flow was reached at an overall shear stress of 175 dynes/cm^2 and, again, at an overall shear stress of 315 dynes/cm^2. This oil, although viscous at this temperature, could not be described as gelled and only had a small yield value. Flow commenced at the flow meter as soon as suction was applied with an initial surge of 0.5 gallon. Increasing flow followed after about three minutes pumping, almost before the initial surge had died away, and steady flow was reached without difficulty. The pressure drop, and hence the shear stress, in each section of the pipe, soon settled at a value which, except for occasional readings, was constant within the anticipated experimental error, but not necessarily the same in each section. The variations in Section 5 to 6 are the most pronounced, partly because it was nearest the pump, and most liable to be affected by slight changes at the valve by which the pressure drop was controlled, and partly because it was the shortest section, so the possible error in calculations of shear stress from pressure drop was largest for this section.

Fig. 6 related to Run 51, in which F.36 oil was pumped at 36°F after 16 days storage. Steady flow was achieved at 280 dynes/cm^2 and then at 390 dynes/cm^2. This oil appeared to have gelled and associated laboratory measurements indicated that it had an appreciable yield value. However, the suction applied was sufficient to set up flow in the line in the first few minutes, the initial surge of 0.6 gallon in the first minute being succeeded by flow increasing from about 0.1 g.p.m., the minimum figure reached, as the initial surge died away. The graphs for flow rate and shear stress during this run follow the same pattern as that shown for Run 55, except for some fluctuations of pressure and shear stress, especially in the sections nearest the pump, when pumping started and when full suction was applied at about 110 minutes. Since the increase in suction took place at the same time as the receiving tank, into which the oil was being discharged, filled up and had to be changed, the pressure fluctuations were unusually large on this occasion.

Fig. 7 shows another example, Run 64, in which the oil ex Kent refinery was pumped at 36.5°F after 26 days storage. On this occasion, 0.5 gallon passed the flow meter in the first minute, as suction was applied and the fuel in the line came under strain. Flow then ceased entirely, for about 10 minutes, then started very slowly. Steady flow was eventually achieved, but there was insufficient oil to permit the run being continued at a higher shear stress. In fact, the run ended when the cold room tank was nearly empty and air was being sucked along the line.

Fig. 8 relates to Run 49, the clearing of a line of F.36 fuel at 36°F, after three days storage, and its displacement by the same fuel at 54°F, which had been pumped into the cold room tank just before the run. Full available suction was applied and, in some sections, this caused shear stresses of about 800 dynes/cm^2. Flow started immediately with 2.45 gallons in the first minute, dropping to a minimum of 0.35 gallons in the fourth minute, then building up steadily. Very high flow rates were reached, as the line was cleared in 18 minutes, and once the line was filled with the warmer oil from the tank, having a viscosity of about 4 poise, the flow rate reached nearly 70 g.p.m. Fig. 8 clearly shows the reduction of pressure drop, and hence shear stress, in the earlier sections of the line as the thin oil displaced the viscous cold oil, the accompanying build-up of shear stress in the last section of the line, and its eventual drop when the thin oil reached that section. There was a reduction in the total pressure drop, and hence average shear stress, in the observed sections as the cold oil left the cold room and the rest of the line, between the cold room and the pump, took up an increasing share of the available pressure drop.

Fig. 9 shows Run 60, a line clearing run, in which the line was gelled, and the shear stress applied was comparable with the yield value of the oil derived from yield value tube measurements. In this instance, the Bahrein fuel was cleared from the line at 32.5°F, after seven days storage, and replaced by the same oil from the cold room tank having a temperature of 67°F and a viscosity of about 4 poise. After the usual initial surge of about half a gallon, flow stopped completely and only re-started very slowly after 25 minutes. The line cleared in 91½ minutes and the flow rate shot up to about 65 g.p.m. as thin oil came right through the line.

This run illustrates the passage of the suction wave down the line as suction was applied at a constant value of about 330 dynes/cm^2 overall. The three sections nearest the pump came under their maximum shear stress of 550 to 600 dynes/cm^2 in the first minute, then the shear stress in these sections decreased as the other two sections came under reduced pressure. Section 2 to 3 reached a maximum shear stress of 460 dynes/cm^2 in 5 minutes; section 1-2, the farthest from the pump, took seven minutes to reach its maximum shear stress of 430 dynes/cm^2. At this stage, the highest shear stresses were in the sections of the pipe farthest from the pump. They then tended slowly to equalise until flow commenced at a rate of about 0.02 g.p.m. after 25 minutes. The remainder of the run followed the pattern already noted in Run 49. As the overall pressure drop was held constant as far as possible until the line cleared, there was an even larger concentration of stress on the length of cold gelled oil as it neared the end of the observed sections and a maximum of 800 dynes/cm^2 was reached in section 5-6. This section also showed some fluctuations between 30 and 45 minutes, when the total volume of oil which had passed the flow meter was between 0.9 and 1.8 gallons; this suggests that the gel structure broke down in this section before it did in the others.

Fig. 10 refers to Run 68, in which F.21 oil was cleared from the line at 36.5°F, after three days storage, and was followed by the same oil at about 50°F. The viscosity of this oil, after it had passed through the pump to the cold room tank and been stored in the cold room for some four hours, until the line was cleared of cold oil, is not known. But it was probably of the order of 40 poise, varying markedly according to the conditions of shear. Yield value measurements having shown that the yield value of this oil would be over 300 dynes/cm^2 and viscosity measurements, under constant shear stress, having confirmed this and indicated that the oil would only move with difficulty, even at 500 dynes/cm^2, maximum suction was used throughout the run. The flow meter passed two gallons in the first four minutes, stopped for about two minutes, then re-started; but it only passed a further two gallons in the next hour. The rate of flow reached 0.1 g.p.m. after 90 minutes and steadily increased thereafter until the line was cleared in 240 minutes.

The overall shear stress was fairly constant for the first three hours at about 450 dynes/cm^2, after which it decreased slightly for about half an hour then more rapidly to a minimum of 235 dynes/cm^2 after a total of four hours. Unlike the two line clearing runs just discussed, at the end of which the line was full of oil at about 4 poise viscosity, reaching the pump at a flow rate approaching the maximum which it could handle at the speed at which it was set, the line on this occasion still contained viscous oil. The overall shear stress in the instrumented sections rose to 400 dynes/cm^2 after the line was cleared; the flow rate was nearly 7 g.p.m., and still rising, when the run was ended after some four and a quarter hours.

The progress of the suction wave alone the line at the beginning of the run was again very pronounced. In the two sections nearest the pump, just over 1000 dynes/cm^2 was reached in two minutes. The other three sections lagged behind and reached maximum shear stress in 10 to 15 minutes. The pattern, thereafter, was as in the other runs, except for periods of low shear stress in sections 4-5 and 5-6. It is considered most likely that the high shear stress nearest the pump, in the first two minutes, caused some movement in these two sections and that the depression in the shear stress graph for section 4-5, during the next half hour, is a result of this. A similar depression of shear stress in section 5-6, between 90 and 120 minutes, and a minor dip in section 4-5, immediately before, may be the result of rupture of the gel in section 5-6 as genuine flow, steady although very slow, commenced at about 90 minutes.

These observations are based on flow rate and pressure drop. Penetration of warm oil down the pipe was also followed by noting temperature changes. The three sets of thermocouples placed across the pipe, near point 1, between points 3 and 4 and near point 6, gave useful verification of the progress of the warm oil. By placing two of the thermocouples in each set at opposite positions near the pipe wall, and one in the centre, it was hoped to detect whether the cold oil passed as a plug, i.e. all three thermocouples reacted simultaneously, or whether the warm front penetrated faster at the centre. The results for Run 49 are shown in Fig. 11. This and also the data from Runs 47, 48 and 50, suggested that the warm oil travelled faster at the side of the pipe next to the central tank of warm oil, than at the side away from the tank. Run 61 and 67, however, indicated the exact opposite. Run 52 moreover, suggested that the warm oil travelled faster down the centre of the pipe than on either side. In Run 52 this may well have been true, as both the flow rate and the pressure distribution indicated that the warm front should have reached the first thermocouples considerably earlier. It is believed that, in this instance, the flow rate for the first four hours was so slow that the warm oil was cooling in the pipe and in the bottom of the tank near the entrance to the pipe.

It had been hoped that clear evidence would be obtained, either of plug flow, or of Newtonian laminar flow, with the oil travelling much faster down the centre of the pipe than at the sides. The results are inconclusive. It it considered most probable that the cold oil moves as a plug, i.e. is extruded rather than flows, at least until it has gathered speed; but that it breaks away from the wall, at start up, less sharply than is envisaged by the usual models of plug flow and that some uneven penetration by the following warmer oil can result.

In one of the later large scale pumping trials, a prototype velocity indicator(21)(22)(23) was inserted in the pipe to determine the velocity distribution across the pipe. This instrument was not used in the work described here, since it would take up too large a part of the cross-section of a four inch pipe, and thus disturb the flow. There is, therefore, no evidence available to indicate the flow pattern, in those runs in which the cold room tank was full of cold oil.

There remains the problem of whether appreciable loss of structure, and hence of viscosity, occurs in the pipe once steady flow conditions have been established. The average shear stress in each section of the pipe, during the periods in each run when steady or near steady flow conditions had been established, are set out in Table 9. In addition, overall shear stresses between points 4 and 6, i.e. the last 51 feet of observed line, are given, since the last section, 5-6, was shorter than any other. In the field trials it was concluded that the bulk of the shearing appeared to take place in the swing arms, the tank valve and the first section of pipe line, since little evidence of breakdown of structure as the oils passed down the rest of the line could be detected. It was hoped that, using shear stresses of around 300 dynes/cm^2, with gelled or near gelled oils at 36°F, evidence of breakdown might have been detected in this rig. The pressure drop per unit length, and hence shear stress, was normally greater in the first section of the pipe than in the last two sections, 4 to 6. But more definite conclusions cannot be drawn. There was a tendency for abnormally high shear stresses to be measured in section 4-5. The reason for this was not clear, but may have been caused by errors in pressure measurements. The normal error of ± 0.2 p.s.i., is equivalent to an average error of ± 50 dynes/cm^2 in measuring shear stress in any one section of the line, and ± 10 dynes/cm^2 over the whole line. This may sometimes have been exceeded.

8. Start up of Pipe Line and the Constant Shear Stress Viscometer

In the field trials at Lyness, a pipeline was allowed to gel, then pumped under the maximum pressure drop available. In spite of the difficulties in arriving at the true flow rate, caused by air in the line between the test sections and the flow meters, it was concluded that there was reasonably good agreement between laboratory and pipe viscosities, from start up until the line had been cleared. For the present purpose, it is simpler to think in terms of rates of shear in the constant shear stress viscometer, and presumed rates of shear in the pipe. The rates of shear obtained using a range of shear stresses are plotted against time of shearing in Fig. 12 for Run 51 (F.36, after 16 days cooling to 36°F).

If the rate of flow in a pipe at start up, does follow, even approximately, the pattern of these rates of shear/time of shearing curves, it may reasonably be expected that a shear stress which is insufficient to cause appreciable flow in a pipe in 30 minutes, the practical limit mentioned in an earlier paragraph, might give a small flow rate after several hours, (c.f. the curves for 400 dynes/cm^2 and 290 dynes/cm^2 in Fig. 12). The rate of flow curves in Fig. 4 do, in fact, approximate to the shape of these graphs, until about half the capacity of the line has been pumped. After that, the flow speeds up rapidly in the line clearing experiments, as the warm oil comes through, or becomes steady as fresh cold oil from the cold room tank fills the pipe.

In Figs. 12 to 14, the rates of shear, presumed to correspond to the flow rates in the pipe, are plotted against time of shearing for Runs 51, 57 and 62, together with constant shear stress viscometer data, at those shear stresses nearest to the shear stress at the pipe wall. In two of these, the viscometer and pipe give rates of shear, at nearly identical shear stresses, which are in good agreement until the line capacity has been pumped (Runs 57 and 62). In the other (Run 51), the line pumped, at 290 dynes/cm^2, at a rate comparable with laboratory measurements at about 325 dynes/cm^2. In Run 54, the oil was too hastily regarded as "unpumpable" at 315 dynes/cm^2, after little oil had flowed in 145 minutes, and a shear stress of 415 dynes/cm^2 was applied. Examination of the data more critically, later showed that some ten gallons had in fact been pumped in the first 145 minutes and that, just before the shear stress was increased, the rate of flow had reached 0.3 g.p.m. and the rate of shear 0.2 sec^{-1}. It is apparent that the pumping team took an unduly pessimistic view of the prospects and rapid flow would not have been long delayed at the first shear stress.

The comparison between pipe and viscometer, in the runs in which pipe and cold room tank were at the same temperature, is summarised in Table 10. Except for Run 64, in which the constant shear stress data is not consistent and an appreciable error may have resulted, the pipe and the constant shear stress viscometer are in good agreement.

The line clearing experiments were not normally accompanied by laboratory viscosity measurements. Data is only available for six runs, one of which (48) is unreliable, owing to the presence of a marked air leak at point 6, with consequent risk of an air lock in the pipe. With the Bahrein oil at 38°F (Run 59) and 32.5°F (Run 60), both described in Fig. 15, the overall shear stress was 320 and 330 dynes/cm^2 respectively, as against the 300 dynes/cm^2 aimed at. Measurable flow, therefore, commenced earlier than would have been predicted by experiments with viscometers at 300 dynes/cm^2. Thereafter, the apparent rate of shear in the pipe, increased more rapidly than rate of shear in the viscometer. Calculation of the shear stress exerted on the length of cold oil in the pipe, showed that it was rising as soon as any significant flow occurred and, when the flow rate rose rapidly, was double the average value over the whole pipe. Similar conclusions were obtained from Run 65 (Kent oil at 32.5°F) and Runs 67 and 68 (F.21 at 36.5°F), the last being shown in Fig.16.

In the next section, the concept of yield value will be discussed in relation to two items of equipment specifically intended for its measurement. It is apparent, however, that if the constant shear stress viscometer gives a reasonable simulation of the change of rate of shear with time, at the start up of a pipeline, it should also be capable of giving the yield value. Therefore, the procedure required, when a set of viscometers is available could simply be to conduct a series of viscosity measurements at progressively lower shear stresses; as the yield value is approached, there will be progressively longer and longer response times before the viscometer starts to rotate and, just below the yield value, the viscometer will fail to start.

The practical difficulties attached to this are, firstly, that just above the yield value the response time may be very long, i.e. hours rather than minutes, and obtaining a true yield value could therefore be extremely tedious and, secondly, viscosity measurements, at shear stresses not much greater than the yield value, are liable to vary considerably owing to inherent experimental error. Such errors are understandable when it is realised that, at start up, a large proportion of the applied shear stress may be absorbed in overcoming the yield value of the oil and only a comparatively small proportion available to produce movement of the viscometer. A further difficulty in these experiments was that a very full programme had to be completed at the time of each run in a limited time; it was therefore not practicable for more than one man to be in the cold room for any length of time, as this was sufficient to affect the temperature of the room. These attempts to find yield value, using the constant shear stress viscometer, had therefore to be fitted into the work scheduled for each day, rather than pursued as a major item in the programme.

The results are set out in Table 11, in terms of the applied shear stress and time in minutes, both for initial movement, i.e. response time, and for the rate of shear to reach 0.1, 0.2, 0.5 and 1.0 sec^{-1}. It was considered, at first, that 60 minutes would be a reasonable period to allow for movement to take place. If none occurred in this time, the stress would be increased. Later, some viscometers were loaded and left much longer than this; overnight, on three occasions.

The yield value of F.36 at 36°F, after nine days storage for Run 47, appeared to be between 300 and 350, probably about 325 dynes/cm^2. The yield value of F.36 at 36°F, after 21 days storage for Run 51, was therefore determined by increasing the shear stress applied to the viscometer by very small amounts. This indicated a yield value certainly greater than 260; probably, about 290 dynes/cm^2.

The Bahrein oil, after 24 days storage for Run 56, was tried at 36°F and the viscometer moved very slowly, both at 150 dynes/cm^2 and when the stress was increased to 200 dynes/cm^2. The yield value was considered to be not much less than 150 dynes/cm^2. More positive evidence was obtained at 37°F after 49 days storage (Run 57). The viscometer did not move overnight at 150 dynes/cm^2, but the stress so strained the gel structure, during this period, that the viscometer turned soon after the stress was increased, to 200 dynes/cm^2, at a rate which was at first greater than that obtained in a separate test at 250 dynes/cm^2. The yield value was considered to be about 175 dynes/cm^2, due to the longer storage period.

The next run which merits individual mention is Run 63, in which the residues from Cell 5 Rosyth were tested at 36°F after 21 days storage. The viscometer indicated a yield value of about 150 dynes/cm^2, but, under 250, 300 (twice) and 350 dynes/cm^2, the experimental error was sufficient to mask the expected increase in rate of shear as shear stress increased. However, this oil was much less homogeneous than normal; it was the sludge from a large stock in which some segregation is believed to have occurred. This may have caused differences in the samples of oil loaded into the viscometer; in particular, different amounts of asphaltic and waxy solid particles.

The Kent oil, at 32.5°F after 21 days storage, yielded in the viscometer when left overnight under 200 dynes/cm^2, but the viscometer was only turning very slowly the next morning. The yield value of the oil was therefore considered to be about 200 dynes/cm^2.

In Run 67, F.21 oil was pumped at 36°F under line clearing conditions after seven days storage. On this occasion, the viscometers were loaded and inspected at infrequent intervals while other work was in hand. Although one viscometer moved in a few minutes at 500 dynes/cm^2 after some hours at 300 and 400 dynes/cm^2 on the day before pumping, the yield value was probably about 500 dynes/cm^2, the comparatively high rate of movement being due to the stress/strain effect mentioned earlier (Run 57).

In Run 68, a line of F.21 at 36.5°F was cleared after only three days storage. One viscometer loaded to 300 dynes/cm^2 did yield during the night, before pumping, but the rate of movement was very small the next morning. A viscometer set at 500 dynes/cm^2, the stress expected to apply to the pipe, only moved very slowly after a response time of about 100 minutes on the day of the run. The yield value was probably between 300 and 500 dynes/cm^2 on the day of the run, as the condition of the oil would still be changing (i.e. the yield value still increasing) after only three days storage.

9. Start-up and Yield Value

The two instruments specifically intended for the measurement of yield value, were the narrow bore yield value tubes, originally described by Gill and Russell, and the C.R.C. tubes as modified at the U.S. Naval Boiler and Turbine Laboratory. The former have been used by A.F.L.A.C. Panel F, with a preliminary heat treatment of the fuel, as a means of predicting yield value of a fuel in storage. The latter, with a different heat treatment, have been used by the U.S. Naval Boiler and Turbine Laboratory, both to predict yield value and to give viscosity data from which flow curves are constructed. Both were installed at the pumping rig and fuel stored in them in the cold room alongside the pipe without any preliminary heat treatment procedure. A dozen yield value tubes could readily be accommodated, but, owing to their size, only four C.R.C. tubes were normally used.

The yield value tubes were used in the manner favoured by A.F.L.A.C. Panel F, in which the stress is increased by 0.5"Hg (i.e. 28 dynes/cm^2) at five minute intervals, starting from 0.5" Hg, until movement of the oil is observed. The stress at which this takes place is known as the yield value. As already demonstrated in the previous section, a fuel may move after being under constant stress for considerably longer than five minutes. Some tubes were therefore subjected to constant stress for up to 30 minutes. If no movement occurred, the stress was increased and the tubes left if need be for another 30 minutes. A yield value could be deduced from these results. This would be lower than that obtained by five minute stress increments and probably not far from the true yield value. Where no tubes had failed to yield after 30 minutes, it was still possible to predict a yield value by plotting the reciprocal of the times before movement occurred at various stresses, against shear stress. The graph so obtained will intercept the shear stress axis at, or about, the true yield value. The results obtained are set out in Table 12. All yield value figures have been rounded off to the nearest ten units.

The C.R.C. tubes were also subjected to increments of stress every five minutes and the stress at which movement was first observed could also be taken as the yield value. In practice, the U.S. Naval Boiler and Turbine Laboratory procedure of fitting an observation pipe filled with methylated spirit to the end of the copper C.R.C. tube and observing, not only initial movement, but also the rate at which the length of oil moves, was followed. The time for movement from the sixth to the twelfth cm mark on the observation tube was used to calculate a rate of shear and viscosity. This was done with a number of tubes, at different shear stresses, and the yield value (i.e. the stress for zero rate of shear) obtained by plotting rheograms of rate of shear against shear stress.

Limited results for a number of runs are given in Table 13. Although the results are few, and repeatability not good when expressed in terms of rate of shear or viscosity, it was possible to estimate yield values for most runs. Run 54 was particularly troublesome, as one of the four determinations must be in error; but it is not possible to decide which one is out of line. It was also found that, as with the constant shear stress viscometer measurements already remarked upon, there was trouble with the residue from Cell 5 Rosyth in Run 63 at 36°F.

The yield values given by the various methods are set out in Table 14, together with start-up data from the pumping runs, expressed in terms of time for initial continuous movement and for the flow rate to reach 0.1 and 0.5 g.p.m. thereafter. Owing to the invariable passage of a small amount of oil past the flow meter, immediately after suction is applied, there is always an apparent movement at once. After this initial flow, little or no flow may take place for some time, until the line yields and continuous flow commences. It was not always possible to obtain reliable results at 0.1 g.p.m. or less. Runs 47 and 48 were troubled by an air leak; Run 63, with the residues from Cell 5 Rosyth, behaved as if there was an obstruction in the pipe, such as sludge or grit deposited from the oil, which suddenly gave way at 55 minutes. Runs 67 and 68 with F.21 did not suffer from this trouble, but the rate of flow built up so slowly, over a long period, that it was almost impossible to decide when the line yielded. The flow data and stress data for Run 68 (Fig. 10) strongly suggest that the shear stress built up in the sections of the pipe nearest the pump, to such an extent that some movement occurred, in these sections, a considerable time before general movement started and this may have been responsible for the very slow trickle of oil in the first 90 minutes. The yielding of a line in sections owing to local high stresses, however caused, has been called "autogenous gel destruction" by Gill and Russell.[17]

It will be seen that none of the methods gives an infallible guide to the start-up of a gelled pipeline. However, it should be remembered that other experience has shown that yield value results may easily suffer from variations of the order of 50 dynes/cm^2 and a high degree of accuracy should not be expected. The behaviour of a pipe line, on start-up, depends not only on the true yield value, but also on the rate at which the gelled structure breaks down once movement commences. The true yield value of an oil in a ship's pipeline may therefore be of no great practical importance. Viscosity data, at around the shear stresses expected to be available in the pipe, is likely to be of more practical significance than measurements of the minimum stress at which the gelled oil in the pipe can be made to yield after an impractically long period of pumping.

It appears that the yield value, as given by either the narrow bore yield value tubes or by the C.R.C. tubes, when applied shear stress is increased every five minutes may be of some use. When the figures, so obtained, were close to the shear stress applied to the pipeline, the pipeline could be expected to take half an hour or more to reach an appreciable flow rate. In some instances, e.g. Run 63 or 70, it took an appreciable time for flow to build up to a satisfactory level, even although the applied shear stress was well above the yield stress as determined by any method. The viscosity data summarised in Table 11 indicated that, in these runs, although the line should yield, it would take time for movement to reach a satisfactory level at the shear stresses it was proposed to use.

The C.R.C. tube is claimed to be superior to the narrow bore yield value tubes, as its width is sufficient to reduce, greatly, the risk of "bridging" across the tube by air bubbles or voids. On the other hand, the narrow bore tubes are much smaller and a number can easily be assembled and used in a limited space. In practice, the operators found no undue difficulty in using either type. The risk of a bad result, with the narrow bore tubes, is considerably reduced if half a dozen are filled, on each occasion, and at least three used in the tests.

The flow curves obtained from the C.R.C. viscosity data are graphs of rate of shear against viscosity on logarithmic paper. Now:-

$$\text{rate of shear} \times \text{viscosity} = \text{shear stress}$$

hence:-

$$\log(\text{rate of shear}) + \log(\text{viscosity}) = \log(\text{shear stress})$$

In a pipeline under constant shear stress, the rate of shear is initially zero, then builds up to a steady value at constant flow rate. The resulting graph of rate of shear against viscosity, on log-log paper, must therefore be a straight line, at 45° to each axis, as in Fig. 17. Plots of rate of shear against viscosity, obtained from C.R.C. tubes at different shear stresses, give lines crossing the pipeline graphs at low shear stresses, since C.R.C. viscosities are measured when the oil has only flowed for a distance equal to between six and twelve diameters of the C.R.C. tube. At this stage, accurate pipe viscosities cannot be expected. Nevertheless, when the data is available, pipe viscosities have been calculated and compared with C.R.C. viscosities, after the oil in the pipe had moved the same number of pipe diameters. The results, in Table 15, indicate that C.R.C. viscosities are, in fact, comparable with pipe viscosities, soon after movement commences. It is,however, considered that the exercise is of little practical value. Viscosities in constant shear stress viscometers are more useful, in that they show whether or not pipe viscosities will be readily reduced at the available shear stress.

10. Steady Flow Conditions and the Constant Rate of Shear Viscometer

Once steady flow is established in a pipeline, the oil is being continuously sheared in its passage down the pipe and its viscosity must be continuously reduced, until it tends towards a constant value. In the early large scale field pumping trials, it was found that reduction in pipe viscosity as the oil passed along the pipe was difficult to detect. This was attributed, partly to the limitations imposed by experimental error, in measuring pressure drops and pipe viscosities, and partly to heavy initial shearing in the swing arms, valves and tank leg, as the oil left the tank and entered the main pipeline. It had been observed that, after an hour or more shearing in a constant rate of shear viscometer, the viscosity of the oil reached a stage at which it was only slowly reduced by further shearing. This stage was never closely defined, but the viscosity at this level was loosely known as the equilibrium viscosity. Pipe viscosities were found to be approximately the same as these equilibrium viscosities.

We have shown in an earlier section and in Table 9 that, under steady flow conditions, the shear stress in the first section of the pipe is, on the whole, significantly greater than in the last sections. There is, therefore, evidence of reduction in pipe viscosity as the oil passes along the pipe. This pipe is, however, much shorter than any large scale pipeline and the residence time of the oil in the pipe is, normally only a matter of minutes. It was, therefore, not surprising to find that pipe viscosities were greater than equilibrium viscosities, calculated from viscometric data by the same methods as were used in the large scale trials. The results obtained, using the Ferranti viscometers, were therefore used to obtain laboratory viscosities at the rates of shear, calculated for each pumping run, after times of shearing equal to the mean residence time of the oil in the pipe under steady flow conditions; and also equal to half the mean residence time. Since Billington(13)(24) observed that viscosity at a given time is inversely proportional to the rate of shear, viscosities could readily be obtained for rates of shear other than those for which direct measurements were available.

The results, set out in Table 16, demonstrate that laboratory viscosities at half mean residence time are in agreement, within experimental error, with pipe viscosities. This has also been expressed graphically in Fig. 18, where it is demonstrated that, in some runs, the agreement is such that graphs of viscosity, against time of shearing in the viscometer, can be directly superimposed upon graphs of pipe viscosity, against distance the oil travels along the pipe.

This observation offered a means of predicting flow rates where only viscosity data is available. There are, however, certain complications, which arise from the now well-known fact that the fuel in the centre of a tank cools much slower than fuel near the top, bottom and sides of a tank; or than fuel in a pipe. If the fuel is only given a limited amount of time to cool, even although the tank may reach the same temperature throughout, the fuel in the centre is likely to be less viscous than fuel near the outside of the pipe; or fuel in beakers, of the same diameter as the pipe. This is demonstrated by the pipe and laboratory viscosity data in Table 16. The nature of the cooling cycle can also effect the result, especially if, owing to deliberate intent or to a fault in the control system, the temperature fluctuates during cooling.

Calculation of probable flow rates using the criterion of viscosity at half mean residence time, when only the available pressure drop and mean shear stress for the pipe are known, is at first sight a complex operation. It is necessary to find the flow rate which gives the rate of shear and mean residence time for which:-

Viscosity x rate of shear = available shear stress

This, however, need not involve a series of trial and error calculations until the correct answer is obtained. There is only one relevant viscosity for each rate of shear, since, if the pipe dimensions are known, the mean residence times for each rate of shear are also known. The first step is therefore to tabulate, as in Table 17, the appropriate viscosities for each viscosity measurement, together with rate of shear and shear stress. This was done for all runs, including that with the Curacao oil, for which Ferranti (constant rate of shear) measurements were available. Shear stress was then plotted against rate of shear as in Figs. 19 and 20; the rates of shear, at the shear stresses actually used in each pumping run, and at 300 and 400 dynes/cm^2, were then obtained from the graphs and flow rates were calculated from these rates of shear (Table 18).

Agreement between calculated and actual flow rates was good. However, certain runs warrant special mention. Firstly, Run 46 in which an increase in shear stress of only 10 dynes/cm^2, gives an increase in rate of shear of 0.7 sec^{-1} , equivalent to almost 1 g.p.m. The viscosity data does not establish the exact position of the graph, especially at 300 dynes/cm^2 and upwards, where the rates of shear in this run were greater than any at which viscosity measurements were possible; errors are possible in the calculated flow rate of about 1 g.p.m. at 145 dynes/cm^2 and 2 to 3 g.p.m. at 400 dynes/cm^2. In Run 53, the actual flow rate was 6.0 g.p.m. at 190 dynes/cm^2, against a calculated 3.9 g.p.m. Shortly before this run, however, the thermostat failed and temperatures rose to 66°F. The tank had only been back at 36°F for a day or two before it was pumped and the centre of the tank would certainly be less viscous than the outer layers. During pumping, moreover, the top oil steadily goes down to the bottom of the tank and remains there as the residue on which the viscosities were measured. In later runs, sample containers were inserted in the tank at various levels before each run, to ensure that samples, representative of other than the top layers, would be available immediately after the runs.

As temperatures decrease, the slope of the shear stress/rate of shear graphs increases until, at 32°F, a change of 10 dynes/cm^2 in shear stress may only change the rate of shear by 0.1 sec^{-1}. We have, however, replaced a possible error in flow rate calculations by another; the pipe and the beakers in the cold room are now likely to be markedly more viscous than the fuel in the centre of the tank, unless the system is allowed several weeks in which to stabilise at the test temperature. The outer parts of the tank may be in a condition nearer that of the oil in the pipe than that in the centre of the tank. Under these conditions, flow rates are intermediate between those calculated from beaker and from tank viscosity data. This was specially noticeable in Runs 56 and 62.

11. The Significance of Arctic Rig Trials

Present instructions are that ships' fuel tanks shall be heated to between 60 and 70°F when sea temperatures fall below 45°F. The situation which might arise, in the event of a ship being flooded as a result of action damage in Arctic waters, would be the results of the effects of time and temperature. To assist in the interpretation of the rig trials, the results are summarised in broad terms in Table 19 compiled from all the evidence available.

The condition of a fuel is primarily dependent on its temperature and its previous thermal history. Fuels cooled from temperatures between 60 and 70°F to some lower temperature are likely to become more viscous, for a time, and then to reach a fairly constant condition. These conditions may be aggravated by heating and cooling cycles, such as the laboratory heat treatments used to produce quickly viscosities such as normally arise only after prolonged storage. Something of this kind appears to have occurred in Run 53, when the F.36 oil, after a preliminary heating to 90°F followed by rapid cooling to 48°F and an inadvertent reheat to 66°F, followed by further cooling to 48°F, was found to be much less viscous at 48°F than the same oil in Run 46 which had merely been brought slowly down to 48°F, from 63°F, and maintained at 48°F until pumped. Run 53 also illustrates another effect of time and temperature, in that the fuel on the top of the tank gave viscosities which corresponded to a lower flow rate than that actually achieved. The oil in the centre of the tank was probably less viscous than that on the top, since it had only been at the test temperature for about two days, whereas the oil on top had been at the test temperature for about six days.

This differential between the fuel in the centre of a tank and that in a smaller container such as a pipe, or beakers of the same diameter as the pipe, occurred in several of the runs at 36°F. Thus, in Run 56, the Bahrein fuel in the tank was, in general, markedly less viscous at 36°F than that in the beakers on the cold room floor after three weeks storage; in Run 57, after seven weeks storage, the fuel in the tank and the fuel in the beakers had practically the same viscosities.

It has been laid down, that in the event of serious damage and flooding, an attempt to re-light the boilers and continue steaming will be made on the same day or, at worst, on the next. It is unlikely that it would be as long as a week before any attempt was made to light up. It is most unlikely that the fuel, throughout a ship's tank, would cool to 36°F from over 60°F in two days. It is therefore probable that the pumping rates achieved or predicted by rig trials, after three weeks at 36°F, are less than those which could be expected from a ship's tank within a week of flooding. However, the condition of the oil in a pipeline in a flooded compartment would be worse than that in a tank, as it would almost certainly reach sea water temperature within two days, if left undisturbed. The results of line clearing runs at 32°F are therefore relevant.

The effect on shear stress of pipe length, pipe diameter, and available pressure drop for various lengths of pipe of 3½ inches to 6 inches diameter, are shown in Table 20. This table gives rates of shear and corresponding rates of flow for pipes of these diameters. A survey of typical ship conditions has indicated that shear stresses of less than 300 $dynes/cm^2$ need not be considered and that available shear stresses will normally be greater, sometimes much greater, than this figure. The minimum flow rate required to light a boiler is roughly equivalent to one tenth full power and may, for the present purpose, be regarded as about 2 g.p.m. in a four inch diameter pipe.

The F.21 fuel is the only one of the six which was unpumpable at 300 $dynes/cm^2$ after less than a week at 36°F. This fuel is well outside the pumpability requirements of any R.N. Specification issued since 1953. The behaviour of the others indicates that all should be pumpable at this temperature and shear stress, after about three weeks storage. It would, however, normally take an hour or more to clear the oil in the line and achieve steady pumping rates. From then the rate would be unlikely to exceed 5 g.p.m. with these fuels and might be as low as 1 g.p.m.

As shown in Table 1, R.N. Specifications for furnace fuel oil used between 1953 and 1962, all relied on flow point (i.e. a pour point determined after a special heat treatment cycle) and a viscosity at 122°F. A fuel having a flow point of 50°F, such as most F.36 fuels, was acceptable provided its viscosity at 122°F was not more than 100 secs. Redwood No. I. The F.36 studied in this programme is an extreme example which failed to meet these requirements. The flow point/viscosity clauses of these specifications were graded, in recognition of the fact that as flow point decreases the rate at which fuels thicken with reduction of temperature also decreases. Thus, under Schedule 390, Specification E. in C. 0-1 and later DEF.2406 Grade 75/50, fuels of up to 300 secs. Redwood I at 122°F were acceptable, provided their flow points did not exceed 30°F. The Curacao fuel used in the trials was of this type.

In the revision of Specification DEF.2406, issued in 1962 as DEF.2406A, these flow point/viscosity clauses have been replaced by a viscosity determination in a Ferranti Portable Viscometer at 48°F, according to the new pumpability test devised by A.F.L.A.C. Panel F[25], although the conventional viscosity determination at 122°F has been retained. The limit at 48°F is 15 poise max; and, at 122°F, 200 and 300 secs, maximum Redwood No. I for grades 50/50 and 75/50 respectively. The F.21 fuel is well outside these limits. It is necessary to consider each of the others, in turn, in order to assess the probable pumpability of the worst fuels which might now be purchased.

The F.36 fuel has a viscosity of 20 poise in the new test at 48°F. This is outside the specification limit of 15 poise maximum by more than the probable reproducibility of the test (3 poise). After three weeks at 36°F, it was still pumpable, under 300 dynes/cm^2, although at about the minimum acceptable rate. But after only two days at 32°F it was practically unpumpable. However, a slightly lighter fuel of this type, meeting the 15 poise limit at 48°F, should be pumpable at an acceptable rate after three weeks at 36°F (i.e. appreciably longer than the time envisaged in emergency) and be capable of being cleared from a line after two days at 32°F.

The Bahrein fuel studied met the flow point/viscosity requirements, although much of the fuel in this consignment did not do so. It just meets the 15 poise limit at 48°F. It is known that this is one of the few oils whose actual viscosities, after long shore storage, sometimes exceed those predicted by the new pumpability test, figures of 23 to 31 poise at 48°F having been found during storage. Its Redwood No. I viscosity of 180 secs. at 122°F is not far below the 200 maximum permitted for Grade 50/50 fuel. In the rig, it was pumpable at 300 dynes/cm^2 after three weeks at 36°F at more than the minimum rate required, and could be cleared from the line after a week at 32°F.

The Kent fuel studied was outside the flow point/viscosity clauses of R.N. Specifications current between 1953 and 1962 and also failed the new pumpability test. The Redwood viscosity of this fuel was 162 secs. at 122°F. It was pumpable in the rig at more than the minimum rate required, both after three weeks at 36°F and after three weeks at 32°F. In view of this it was not considered necessary to carry out rig trials of the less viscous fuel, typical of most deliveries from this refinery.

The residue from Cell 5 Rosyth was worse than the Kent fuel, both in terms of flow point/viscosity and of the new pumpability test, in which latter it had a viscosity of about 30 poise; the precise figure is doubtful owing to its heterogeneity, mentioned earlier. Nevertheless, it was pumpable at a slow rate after three weeks at 36°F. As it did not represent either the bulk oil in the storage cell from which it came, nor any fuel likely to be received in future, it was not studied further.

Many of the grade 75/50 fuels, having Redwood viscosities between 200 and 300 secs. at 122°F, have flow points of 0°F or less and are likely to remain readily pumpable down to 32°F. Other consignments, such as the Curacao fuel studied, have flow points between 0 F and 15 F and a few may have flow points of $30^{\circ}F$ (the maximum permitted in this viscosity range). Owing to the limited quantity available, the Curacao fuel was not actually pumped, but various measurements on the fuel stored in the cold room indicated that it should be pumpable, although at a slow rate, after 18 days at $36^{\circ}F$ or 8 days at $32^{\circ}F$. This fuel also had a viscosity greater than 30 poise in the new pumpability test and future deliveries within the specification limit should therefore be more pumpable in any emergency of the type envisaged.

It is considered, in the light of these trials, that fuels having viscosities of up to 15 poise at $48^{\circ}F$ in the new R.N. pumpability test, should be pumpable at the minimum rate required in an emergency. Owing to the effects of time and temperature, the quicker pumping is attempted, after damage to the ship and ingress of cold water, the better is the chance of clearing fuel lines and achieving useful rates of fuel transfer. Satisfactory flow rates should not be expected immediately pumping a cold line is attempted. It may take an hour or more to get adequate flow in a "flooded" pipeline under the worst combinations of time and temperature, with no suction available to clear it.

Various attempts to hold ship trials of furnace fuel oil pumpability have been made in the past, and a satisfactory trial has not yet been possible. It is considered that the work with this laboratory pumping rig has provided sufficient information, so that sea trials are no longer essential. Any further information which may be required on different fuel supplies can probably be obtained by laboratory measurements, supplemented by work on the rig.

12. Summary and Conclusions

(a) Although the behaviour of a gelled oil in a pipe when pumping is attempted must depend, not only on yield value, but also on viscosity once movement commences, the A.F.L.A.C. yield value procedure does, in general, give an indication of whether flow will occur at a significant rate in an hour or less.

(b) The C.R.C. tubes do not in practice offer any advantages over the narrow yield value tubes and are more unwieldy than the small tubes; the constant shear stress viscometer gives more useful viscosity data than the C.R.C. tube.

(c) The displacement of cold gelled oil in a pipe by warmer fluid oil takes place on an uneven front, rather than the sharp line assumed in descriptions of plug flow.

(d) Although, in general, the yielding of a gelled line is a time dependent phenomenon, governed by the time required for the whole gel to become strained to the state in which flow can commence, uneven stresses may sometimes occur which cause the line to yield in sections. (Gill and Russell's "Autogenous Gel Destruction").

(e) When pumping commences, there is invariably an initial surge, probably caused by the expansion of trapped air bubbles, or even the coming out of solution of dissolved air in the line under vacuum, which does not correspond with conditions further along the pipe.

(f) If this initial surge is discounted the increase in flow rate on starting to pump out a pipe, full of cold oil whether fluid or gelled, is very similar to the increase in rate of shear when the oil is sheared in a co-axial cylinder viscometer at the constant shear stress applied to the pipe.

(g) Owing to continual shearing as the oil passes along the pipe, shear stresses and pipe viscosities at the beginning of the pipe are likely to be higher than at the end nearest the pump.

(h) Pipe viscosities, after steady flow has been established, are comparable with laboratory viscosities determined in a co-axial cylinder viscometer at the rate of shear which would exist in the pipe if flow were Newtonian in character. Pipe and laboratory viscosities are in good agreement, if laboratory viscosities are taken after a time of shearing equal to half the mean residence time of the oil in the pipe.

(i) If the dimensions of a pipe and the available pressure drop are known, the available shear stress, and also the mean residence time of the oil in the pipe at any rate of shear, can readily be calculated. From this, viscosities and shear stresses at half mean residence time for various rates of shear can be obtained in constant rate of shear viscometers. From rheograms of shear stress/rate of shear, under these conditions, probable flow rate in the pipe can be deduced.

(j) Only the F.21 fuel, which represents a type well outside current R.N. pumpability requirements, could rapidly become unpumpable at 36°F under 300 dynes/cm^2.

(k) Fuels meeting, or only a little outside, current R.N. pumpability requirements, should be pumpable under 300 dynes/cm^2 after two or three weeks at 36°F. Although the pumping rates achievable may be well below full power, they should be greater than 1/10th full power.

(l) It should be possible to clear a line of fuel meeting, or just outside, current R.N. pumpability requirements, under a shear stress of 300 dynes/cm^2 after two or three days at 32°F. After a week under these conditions, some borderline fuels may be very difficult to move or practically unpumpable. The F.36 fuel, which was very difficult to pump after two days at 32°F, does not meet present specification requirements.

(m) The sooner pumping is attempted after damage and flooding, the better the chance of achieving a satisfactory fuel transfer rate. If the lines have been in ice cold water for a considerable time (e.g. more than a day) pumping for an hour or more may be required to achieve a satisfactory flow rate.

(n) There is now no need for ship trials of fuel oil pumpability in Arctic waters. It should be possible adequately to assess any unusual fuels in the laboratory, possibly supplemented by work in the pumping rig.

13. <u>Acknowledgments</u>

The authors express their thanks to all persons who have assisted in the work reported here. The original broad design for the rig was proposed by members of the Admiralty Fuel and Lubricants Advisory Committee, the detailed design and actual construction being the responsibility of A. J. S. Baker, then on the staff of the Admiralty Oil Laboratory. It has been operated with the assistance of the authors' colleagues, especially C. J. Spilman and M. J. Willis, who have been regular members of the Admiralty Oil Laboratory trials team.

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TABLE 1

Extract of Furnace Fuel Oil Specifications 1939 to 1962

	1939	1940	1940 (Later Spec.)	1943 Wartime Relaxations	1949 Sched. 385	Interim Specification	E. of C. 0-1 - Dec. 1953 Sched. 390 DEF 2406* Grade 50/50 July, 1958	E. of C. 0-1 June, 1954 Sched. 390A DEF 2406* Grade 75/50 July, 1958	U.S.N. Special MIL-F-859D
Viscosity Redwood No. 1 secs. at 32°F. (Max.).	10,000 (Trinidad)	-	-	-					
40°F	10,000 (Abadan)	-	-	-	Possibly a Gell				
70°F	270†	1200	1500	1500					
100°F	130†	400	450	450					
122°F	86†	220†	220†	220†	300	Flow Point Viscosity >30°F 100 <30°F 300	Flow Point Viscosity 45-50°F 100 35-40°F 175 <30°F 300	Flow Point Viscosity 45-50°F 100 35-40°F 175 <30°F 200	200‡
Pour Point or Flow Point, °F	Oil subjected to Admiralty Bottle Test		Bottle Test withdrawn	Not Specified		Flow Point 50°F. max. (Method 7)	Flow Point 50 F. max. (Method 7)	Flow Point 50 F. max. (Method 7)	Pour Point 15ø
Specific gravity at 60°F. (Max.)		Not specified		0.990	0.985	0.99	0.99	0.99	0.99
Sulphur (Max.)	1.5	1.5	1.75	2.5	3.5	3.5	3.5	3.5	3.5
Flash Point °F (Min.)	175	175	175	150	150	150	150	150	150

* DEF.2406A late 1962 will use the new pumpability test with a maximum of 15 poise at 48°F for both grades in place of these flow point/viscosity clauses. The maximum viscosity at 122°F for grade 75/50 being 300 secs. Redwood I and for grade 50/50 200 secs. Redwood I.

† Values obtained by interpolation.

‡ Values obtained by conversion from Saybolt Viscosity.

ø If the Pour Point exceeds 15°F then oil must pass a Maximum Fluidity Test at 32°F. (P. & O. Test).

TABLE 2. Fuels Studied in the Laboratory Pumping Rig

Type or Source	Persian F.36	Persian F.21	Bahrein	Caribbean & Venezuelan area	U.K. Refined Middle East crude	U.K. Refined	
Refinery	Abadan	Abadan	Bahrein	Curacao	Kent	Kent and Stanlow	
Stored in depot	Killingholme	Killingholme	Invergordon	Killingholme	Killingholme	Rosyth	
Received in depot in	March 1951 April 1951	March 1948 March 1950	July 1954	August 1948	July 1954	Mid 1955	
Stored until	Late 1957	Late 1957	October 1957	Late 1957	Late 1957	Dec.1958/Jan.1959	
in Tank No.	7	38	40	50	8	-	
Underground Cell No.	-	-	-	-	-	5	
						Bulk Oil	Residue[ø] used in Rig
Specific gravity 60/60°F	0.919	0.926	0.943	0.928	0.930	0.930	-
Viscosity at 122°F secs Redwood I	110-120	170	180	250	162	170	180
Flow point, °F	50	70	30	10	45	35	45
Sulphur, %	1.8	2.7	2.8	1.7	3.2	3.2	-
Asphaltenes, %	1.9	1.2	-	1.5	1.1	-	-
Wax, %	9.2	11.5	-	9.4	9.8	-	-
Supplied against specification	Schedule 385	Schedule 385	U.S.N.Special with pour point waiver	Schedule 385	"Off spec" tank of Schedule 390	Schedule 390A	
Viscosity at 48°F given by new pumpability test - poise*	20	Greater than 30	15[ƒ]	About 30	25	-	Greater than 30
Rating in terms of Spec.DEF.2406 (Flow point/Viscosity clauses)	Fails to meet pumpability limits	Well outside pumpability limits	Grade 50/50	Grade 75/50	Fails to meet pumpability limits	Residue Fails to meet pumpability limits	
Rating in terms of Spec.DEF.2406A (New Pumpability Test. 15 poise max.)	Fail	Fail	Grade 50/50	Fail	Fail	-	Residue Fails

ø Oil from Cell 5 Rosyth was taken in January 1959 for Arctic Pumping Trials in R.F.A. Tidereach. It was found that the residue remaining in Cell 5 was considerably thicker than this oil. The residue was selected for trials in the laboratory pumping rig.

* D.E.F. Method in press. The development of the test was described in the I.P. Symposium on Flow Properties of Admiralty Fuel Oils(25).

ƒ This oil became considerably thicker after storage in the U.K. than the figure predicted by the pumpability test.

TABLE 3

SUMMARY OF LINE CLEARING RUNS

WITH F-36

Run No,	Date	Line Temp.	Thermal History		Time before pumping days	Temp. of oil pumped into cold room tank on day of run °F	Overall Shear Stress		Time in mins. to reach flow rate of		
			Temp. of oil on filling °F	Time to reach test temp.			Aimed at dynes/cm^2	Achieved dynes/cm^2	½ g.p.m.	1 g.p.m.	5 g.p.
47	8.10.58	36	61	About 14 hrs.	9	52	Maximum available	Nearly 600 falling as flow commenced	>15 No other records as seriou air leak developed at glan	-	-
48	21.10.58	36	63	About 12 hrs.	7	52	Maximum available	About 575 falling as flow commenced	50	56	60
49	10.11.58	36	55	About 24 hrs. but within 2° in about 12 hrs.	3	54	Maximum available	About 575 falling as flow commenced	7	9	14
50	13.11.58	36	49	About 8 hrs.	3	46	300	315 ± 10	30	45	54
52	12.12.58	32	62 Maintained at about 60°F over night before commencing to cool.	About 30 hrs. but within 2° in about 15 hours.	2	46	300	290 ± 25	220 Took 140 mins, to reach 1/	260	283

TABLE 3

SUMMARY OF LINE CLEARING RUNS

WITH F-36

oh .	Time before pumping days	Temp. of oil pumped into cold room tank on day of run °F	Overall Shear Stress		Time in mins. to reach flow rate of			Time in Mins. to Clear Line	Conditions in line a few minutes after line cleared		Remarks
			Aimed at dynes/cm²	Achieved dynes/cm²	½ g.p.m.	1 g.p.m.	5 g.p.m.		Rate of Flow g.p.m.	Shear Stress dynes/cm²	
s.	9	52	Maximum available	Nearly 600 falling as flow commenced	>15	-	-	-	-	-	
					No other records as serious air leak developed at gland.						
s.	7	52	Maximum available	About 575 falling as flow commenced	50	56	60	61	About 50	About 250	Pressure drop in line changes rapidly as gelled oil is cleared out. Air leak not completely cured.
).)o	3	54	Maximum available	About 575 falling as flow commenced	7	9	14	18	About 70	About 250	Pressure drop in line changes rapidly as gelled oil is cleared out.
	3	46	300	315 ± 10	30	45	54	58	About 54	About 275	
). o	2	46	300	290 ± 25	220	260	283	285	About 22	About 320	Immediately after the line cleared the temp. of the oil coming from the cold room tank dropped from 46°F to about 40°F.
					Took 140 mins, to reach 1/10 g.p.m.						

T A B L E   4

Summary of Runs with F-36 in which both Line and Tank in Cold Room were Filled and Cooled

Run No.	Date	Temperature °F: Line Temp. °F	Temperature °F: Cold Room Tank	Thermal History: Temp. of oil on filling	Thermal History: Time to cool to test temp.: Line	Thermal History: Time to cool to test temp.: Tank Centre	Thermal History: Time before pumping days	Overall shear stress: Aimed at dynes/cm²	Overall shear stress: Achieved dynes/cm²	Time in mins. to reach flow rate of: ½ g.p.m.	Time in mins. to reach flow rate of: 1 g.p.m.	Time in mins. to reach flow rate of: 5 g.p.m.	Time in mins. to Pump Line Capacity
42	9.8.57	35 to 35.5	35 to 38	Probably about 60°F	About 4 days For first three days cold room set at 50°F	Not at 35°F after 14 days	14	Maximum available	550 falling as flow commenced	6 Line filled first with oil at 36°F then temp. rose to 38°F.	8	17	22
43	10.9.57	37.5	37.5 to 38	Probably about 60°F	-	-	21	Maximum available	580 falling as flow commenced	10	11	18	26
45 A test of ability to control shear stress	31.7.58	36	36	No record: oil had been in cold room at temps. between 36 - 70°F for some months.			7 after control set for 36°F	150 200 300 (For ten mins.) 350	155 ± 20 200 ± 20 350 ± 25 except for few mins. at 400	No flow in 20 mins. No flow in 25 mins. Flow commenced at less than 0.2 g.p.m. 18 Time taken from raising shear stress to 300 dynes/cm²	22	-	52
46	16.9.58	48	48	63°F	18 hrs. but within 2° in 8 hrs.	11 days	25	150 Till steady flow achieved 300 (For 6 mins. only)	145 ± 12 Approx.300	1 -	2 -	6 -	16 -
51	3.12.58	35.5 to 36	35.5 to 36	55°F	About 24 hrs.	About 8 days	16	(1) 300 (2) Max. Available	290 ± 15 About 400	25 -	44 -	- -	75 -
53	14.1.59	46.5	46 to 48	95°F	Cooled to 48°F then temp. rose to 66°F on 15th day owing to breakdown. Reset back at 48°F in About 12 hrs.	About 4 days	21	(1) 150 (2) 200	135 ± 5 180 ± 15	Flow only reached 0.2 gpm in 66 min. 82 Line between cold room and pump at about 32°F believed to be governing flow in first 150 mins.	102	150	130
54	25.2.59	37	35.75 to 36.25	95°F	About 7 days	About 13 days	23	300 400 300	315 ± 10 415 ± 15 330 ± 10	More than 145 minutes	20	55	45

TABLE 4

Runs with F-36 in which both Line and Tank in Cold Room were Filled and Cooled Together

1 History		Overall shear stress		Time in mins. to reach flow rate of			Time in mins. to Pump. Line Capacity	Conditions once steady flow had been established				
to cool est temp. Tank Centre	Time before pumping days	Aimed at dynes/cm^2	Achieved dynes/cm^2	$\frac{1}{2}$ g.p.m.	1 g.p.m.	5 g.p.m.		Flow rate g.p.m.	Rate of Shear sec^{-1}	Shear stress dynes/cm^2	Pipe viscosity poise	Temp. °F
Not at 35°F after 14 days irst three old room t 50°F	14	Maximum available	550 falling as flow commenced	6	8	17	22	8.1	5.9	425	73	37.5
				Line filled first with oil at 36°F then temp. rose to 38°F.				7.6	5.5	420	77	38
								7.2	5.2	410	79	38
-	21	Maximum available	580 falling as flow commenced	10	11	18	26	7.7	5.6	455	81	38
had been temps. F for	7 after control set for 36°F	150	155 ± 20	No flow in 20 mins.				-	-	-	-	-
		200	200 ± 20	No flow in 25 mins.				-	-	-	-	-
		300 (For ten mins.)		Flow commenced at less than 0.2 g.p.m.				-	-	-	-	-
		350	350 ± 25 except for few mins. at 400	18	22	-	52	2.7	2.0	345	173	36
				Time taken from raising shear stress to 300 dynes/cm^2								
11 days	25	150	145 ± 12 Till steady flow achieved	1	2	6	16	9.4	6.9	145	21	48
		300 (For 6 mins. only)	Approx.300	-	-	-	-	About 36	About 26	About 300	About 11	48
								(Insufficient oil available)				
About 8 days	16	(1) 300	290 ± 15	25	44	-	75	3.2	2.4	280	120	36
		(2) Max. Available	About 400	-	-	-	-	6.6	4.9	390	79	36
to 48°F mp. rose F on 15th ving to own. Rem t 48°F in About 4 days	21	(1) 150	135 ± 5	Flow only reached 0.2 gpm in 66 min.				-	-	-	-	-
		(2) 200	180 ± 15	82	102	150	130	6.0	4.4	190	43	48
				Line between cold room and pump at about 32°F believed to be governing flow in first 150 mins.								
About 13 days	23	300	315 ± 10	More than 145 minutes								37
		400	415 ± 15		20	55	45	5.0	3.7	415	111	37
		300	330 ± 10					2.6	1.9	325	171	37

TABLE 5

Summary of Runs with Bahrein Fuel

Run No.	Date	Line Temp. °F	Thermal History: Temp. of oil on filling	Thermal History: Time to reach Test Temp.	Thermal History: Time before Pumping days	Temp. of oil pumped into cold room on day of run °F	Overall Shear Stress: Aimed at dynes/cm^2	Overall Shear Stress: Achieved dynes/cm^2	Time in mins. to reach flow Rate of: $\frac{1}{2}$ g.p.m.	Time in mins. to reach flow Rate of: 1 g.p.m.	Time in mins. to reach flow Rate of: 5 g.p.m.	Time to Clear Line mins.	Condition once steady flow was established: Rate of Flow g.p.m.	Condition once steady flow was established: Shear Stress dynes/cm^2	Condition once steady flow was established: Rate of Shear sec^{-1}	Condition once steady flow was established: Pipe Viscosity poise
55	7.4.59	47.5	77°F	4 days	21	-	150	175 ± 10	4	5	21	22	5.2	175	3.9	45
						-	300	315 ± 5	-	-	-	-	15.9	315	11.8	27
56	30.4.59	36	55°F	10 days	24	-	300	315 ± 15	34	42	-	66	3.6	320	2.9	110
						-	400	390 ± 10	-	-	4	12	6.5	390	4.8	81
57	24.6.59	36	68°F	6 days	49	-	300	320 ± 15	117	138	-	166	2.23	320	1.65	194
						-	400	400 ± 15	-	-	-	-	3.80	395	2.8	141
58	29.6.59	36	62°F	36 hrs.	3	73	300	290	3	6	15	18	about 60	290	Line clearing runs. Rates of flow and shear stresses as a few minutes after line cleared.	
59	9.7.59	38	68°F	36 hrs.	8	75	300	320	8	10	15	18	about 60	170		
60	20.7.59	32.5	65°F	30 hrs.	7	67	300	330	63	80	89	91½	about 60	220		
61	22.7.59	32	62°F	12 hrs.	2	68	300	305	28	37	51	52½	about 60	240	Steady flow not achieved after line cleared.	

TABLE 6

Summary of Runs with Residues from Cell 5, Rosyth

Run No.	Date	Line Temp. °F	Thermal History			Overall Shear Stress		Time in minutes to reach flow rate of			Time to clear line mins.	Condition once steady flow was established			
			Temp. of oil on filling °F	Time to reach Test Temp.	Time before Pumping days	Aimed at dynes/cm²	Achieved dynes/cm²	½ g.p.m.	1 g.p.m.	5 g.p.m.		Rate of Flow g.p.m.	Shear Stress dynes/cm²	Rate of Shear sec⁻¹	Pipe Viscosity poise
62	2.9.59	43.5	64	8 days to reach 52°. Maintained at 52° for 7 days. Cooled in 10 days to 44°F. Pumped 5 days later.	30	130 330	110 ± 10 300 ± 5	208	274	-	264	1.4 10.4	115 305	1.04 7.7	111 40
63	7.10.59	36	57	24 hours	21	300 400	280 ± 10 370 ± 5	60	75	-	115	1.75 3.6	280 375	1.3 2.65	216 142

1

TABLE 7

Summary of Runs with Kent oil ex Tank 8 Killingholme

Run No.	Date	Line Temp. °F	Thermal History			Temp. of oil pumped into cold room tank on day of run °F	Overall Shear Stress		Time in mins., to reach flow rate of		
			Temp. of oil on filling °F	Time to reach test temp.	Time before pumping days		Aimed at dynes/cm²	Achieved dynes/cm²	½ g.p.m.	1 g.p.m.	5 g
64	18.5.60	36.5	65	Pipe within 2° in 12 hrs. Tank 4 days	26	-	300	285 ± 10	31	38	·
65	10.6.60	32.5	45-50	12 hrs. then Unit control failed. 7 days at 40°F, reset 12 hrs. to 32°F	22 14 at test temp.	About 55	300	280 ± 10	17	24	3
66	4.7.60	32.5	58	Tank 3½ days Pipe no record	21	-	300	285 ± 15	95	133	-

TABLE 8

Summary of Runs with F-21 Oil ex Tank 38 Killingholme

Run No.	Date	Line Temp. °F	Thermal History			Temp. of oil pumped into cold room tank on day of run °F	Overall Shear Stress		Time in mins. to reach flow rate of		
			Temp. of oil on filling °F	Time to reach test temp.	Time before pumping days		Aimed at dynes/cm²	Achieved dynes/cm²	½ g.p.m.	1 g.p.m.	5
67	5.10.60	36.5	55	12 hrs.	7	About 50	Maximum available	490 ± 10 for first 175 min. 380 at 400 min. 210 at 445 min.	410	435	
68	13.10.60	36.5	58	1 day	3	About 50	Maximum available	455 ± 10 for first 150 min. 400 at 210 min. 235 at 247 min.	214	235	2
69/1	19.10.60	Start 36 end 37.5	75	1½ days	6	Probably about 50	300	310 ± 10	No flow in 360 min after initial surg		
69/2	20.10.60	Start 36 end 37	-	Same filling	7	-	Maximum available	520 ± 20	No flow after init surge		
69/3	21.10.60	40	Heating overnight to raise line to 40	Same filling	8	-	Maximum available	550 ± 10 for 20 min. falling to 450 in 70 min. & 390 in 130 min.	70	100	1
70	23.11.60	50	Pipe & cold room tank filled at same time at about 55		29	-	300	310 ± 10	285	315	

T A B L E 7

Summary of Runs with Kent oil ex Tank 8 Killingholme

story		Temp. of oil pumped into cold room tank on day of run °F	Overall Shear Stress		Time in mins.. to reach flow rate of			Time to Clear Line mins.	Conditions once steady flow was established			
e to ach temp.	Time before pumping days		Aimed at dynes/cm^2	Achieved dynes/cm^2	½ g.p.m.	1 g.p.m.	5 g.p.m.		Rate of Flow g.p.m.	Shear Stress dynes/cm^2	Rate of Shear sec^{-1}	Pipe Viscosity Poise
within 2 hrs. 4 days	26	-	300	285 ± 10	31	38	-	63	4.1	285	3.0	95
s. then ontrol l. s at reset s. to °F	22 14 at test temp.	About 55	300	280 ± 10	17	24	37½	41½	About 37	Line clearing		
½ days no d	21	-	300	285 ± 15	95	133	-	156	Approaching steady state 2.7	300	2.0	150
									Highest shear stress in later stages and flow still increasing slowly until tank emptied.			

T A B L E 8

Summary of Runs with F-21 Oil ex Tank 38 Killingholme

tory		Temp. of oil pumped into cold room tank on day of run °F	Overall Shear Stress		Time in mins. to reach flow rate of			Time to Clear Line mins.	Conditions a few minutes after line was cleared.			
to ch temp.	Time before pumping days		Aimed at dynes/cm^2	Achieved dynes/cm^2	½ g.p.m.	1 g.p.m.	5 g.p.m.		Rate of Flow g.p.m.	Shear Stress dynes/cm^2	Rate of Shear sec^{-1}	Pipe Viscosity Poise
rs.	7	About 50	Maximum available	490 ± 10 for first 175 min. 380 at 400 min, 210 at 445 min.	410	435	-	440	About 4	390	Line Clearing	
ay	3	About 50	Maximum available	455 ± 10 for first 150 min. 400 at 210 min. 235 at 247 min.	214	235	251	245	About 7	400	Line Clearing	
ys	6	Probably about 50	300	310 ± 10	No flow in 360 mins. after initial surge.				-	-	Line Clearing	
, ig	7	-	Maximum available	520 ± 20	No flow after initial surge				-	-	Line Clearing	
, ig	8	-	Maximum available	550 ± 10 for 20 min. falling to 450 in 70 min. & 390 in 130 min.	70	100	135	125	About 5	390		
									Oil from cold room tank came through at 43°F to 46°F.			
	29	-	300	310 ± 10	285	315	-	330	Final readings before cold room tank empty 2.0	325	1.5	220
									Did not reach steady state			

T A B L E 9

SHEAR STRESS ALONG THE PIPE UNDER STEADY FLOW

Run No.	Temp. °F	Oil	Shear Stress, dynes/cm² Section							Rate of Flow g.p.m.
			1-2	2-3	3-4	4-5	5-6	4-6	1-6	
42	38	F.36	550	420	380	470	200	360	410	7.2
43	38		510	430	480	520	340	450	455	7.7
45	36		520	340	390	340	130	260	345	2.7
46	48		150	160	190	130	140	130	145	9.4
51	36		260	310	290	310	210	270	280	3.2
51	36		410	440	350	420	290	360	390	6.6
53	48		130	180	250	190	200	190	190	6.0
54	37		530	470	380	280	370	380	415	5.0
54	37		440	340	300	270	320	290	325	2.6
55	47.5	Bahrein	290	150	170	160	130	150	175	5.2
55	47.5		400	360	290	310	200	270	315	15.9
56	36		420	340	310	340	200	280	320	3.6
56	36		460	420	350	390	300	350	390	6.5
57	36		380	240	220	460	290	390	320	2.2
57	36		450	340	270	540	310	450	395	3.8
62	43.5	Cell 5 Residue	130	100	160	70	-	-	115*	1.4
62	43.5		330	260	380	260	-	-	305*	10.2
63	36		330	280	270	260	-	-	280*	1.8
63	36		400	400	360	350	-	-	375*	3.6
64	36.5	Kent	330	300	290	280	230	260	285	4.1
66	32.5		380	320	250	310	260	290	300	2.7

* 1-5, tranducer at point 6 faulty.

TABLE 10

Comparison of Conditions in Pipe and in

Constant Shear Stress Viscometer

Run No.	Temperature, °F	Shear Stress in Pipe dynes/cm^2	Shear Stress in Viscometer which gives same pattern until line is cleared
46	48	145 ± 12	about 150 dynes/cm^2
51	36	290 ± 15	about 325 "
54	37	315 ± 10 (then 415)	about 280? " (then 400) "
55	47.5	175 ± 10	about 175 "
56	36	315 ± 15	about 330 "
57	36	320 ± 15	300 "
62	43.5	110 ± 10	100 "
63	36	280 ± 10	about 280 "
64	36.5	285 ± 10	about 200 "
66	32.5	285 ± 15	about 250 "
70	50	300 ± 10	about 275 "

TABLE 11

An Estimation of Yield Values

from Constant Shear Stress Viscometers

Run No.	Oil	Temp. °F	Shear Stress dynes/cm²	Time for Initial Movement mins.	Time to reach a rate of shear of 0.1 sec⁻¹ mins.	0.2 sec⁻¹ mins.	0.5 sec⁻¹ mins.	1.0 sec⁻¹ mins.	Probable Yield Value dynes/cm²
47	F.36	36	300 then	>60	Stress increased at 60 mins.				
			350	21	≃25	≃30	50	72	
			400	<5	5	15	53	81	
			500	<5	<5	6	11	18	About 325
48	F.36	36	400	<8	15	25	35	45	Well below 400
51	F.36	36	260	>60	Stress increased at 60 mins.				
			268	>30	"	"	" 30	"	
			275	>30	"	"	" 30	"	
			290	<20	>60	-	-	-	
			300	18	44	70	105	≃135	
			300	18	23	30	49	96	
			350	5	5	7	14	30	290
54	F.36	37	300	≃20	32	41	86	-	
			400	<5	7	9	20	36	Less than 300
55	Bahrein	47.5	100	<2	5	7	14	16	Well below 100
56	Bahrein	36	150	25	>65 Stress increased at 65				
			200	-	38	82	175	210	
			250	<10	43	49	69	90	Less than 150
57	Bahrein	37	150	>980	Stress increased at 980				
			200	<5	71	145	>210	-	
			250	<19	95	145	165	180	About 175
59	Bahrein	38	150	10	>285	-	-	-	
			300	6	21	25	30	35	
			300	<1	11	13	19	29	Less than 150
60	Bahrein	32.5	250	>60	Stress increased at 60				
			275	30	>130	-	-	-	
			300	22	110	135	>200	-	
			300	<10	83	98	140	160	About 275
62	Cell 5 Residues	44	100	<5	120	170	>217	-	
			125	<5	18	36	83	145	
			150	<5	≃5	11	35	66	
			200	<1	<2	2	4	6	Less than 100
63	Cell 5 Residues	36	150	63	>270	-	-	-	
			200	<1	170	>185	-	-	
			250	<4	20	29	43	63	
			300	<2	20	32	47	66	
			300	<1	27	45	69	91	
			350	<1	18	25	46	69	
			400	<1	16	22	28	34	About 150
64	Kent	36	200	<1	8	10	19	32	
			300	<1	<5	<5	7	9	Well below 200

TABLE 11 (Cont'd)

Run No.	Oil	Temp. °F	Shear Stress dynes/cm²	Time for Initial Movement mins.	Time to reach a rate of shear of 0.1 sec^{-1} mins.	0.2 sec^{-1} mins.	0.5 sec^{-1} mins.	1.0 sec^{-1} mins.	Probable Yield Value dynes/cm²
65	Kent	32.5	200	31	>31	-	-	-	
			300	< 1	8	18	34	39	Less than 200
66	Kent	32.5	200	<1000	<1000	Yielded overnight			
			250	< 3	28	66	>110	-	
			300	< 5	12	-	20	25	
			400	< 1	4	5	7	9	About 200
67	F.21	36	300	> 280	Stress increased at 280				
			400	> 100	Stress increased at 100				
			500	< 10	> 80	(Day before pumping)			
			500	>180 <250	420	550	>600	-	
			600	< 1	60	200	>420	-	About 500
68	F.21 (only 3 days storage)	36.5	300	>180 <1200	>1200	Yielded on night before pumping.			
			500	≃ 100	190	295	460	-	Between 300 and 500 at time of pumping.
			600	≃ 40	75	115	170	320	
70	F.21	50	200	> 35	-	-	-	-	
				< 75	>420	-	-	-	
			300	4	< 30	63	128	165	
			300	< 1	66	138	240	>260	
			400	<10	44	49	65	88	Less than 200
No Run 18 days storage in viscometer.	Curacao	36	150	< 2	8	16	40	>210	
			200	< 1	3	4	10	60	
			300	< 1	< 2	< 2	< 2	2	
			400	< 1	< 1	< 1	< 1	1	Less than 150
No Run 8 days storage in viscometer.	Curacao	32	200	< 1	< 1	< 1	5	>200	
			300	< 1	< 1	< 1	< 1	1	Less than 200

TABLE 12

Yield Values from Narrow Bore Yield Value Tubes

Run No.	Oil	Temp. °F	Yield Value using AFLAC Method (stress increased every 5 minutes)		Yield Value using Constant Shear Stresses for up to 30 minutes		
			Individual Results dynes/cm²	Mean dynes/cm²	Shear Stress dynes/cm²	Time to Movement (mins)	Yield Value dynes/cm²
46	F.36	48	60; 90; 60	70	30 60	>41 15; 6; 7	60
47		36	200; 170; 200	190	140 170	30 9; 8	140
48		36	230;170;230;230	220	-		-
51		36	230; 200; 200	210	110 140 170 200	>30 29; 33 21; 8 2; 3	140
54		37	280;340;320;340	320	-	-	-
55	Bährein	47.5	60; 60; 60; 60	60	-	-	-
56		36	320;280;280;230	280	170	7; 23	>170
57		37	370;280;340;260	310	170 230 (After Nil at 170 & 200 260	>30 28 1	230
59		32.5	170; 170; 120	150	110 90 170	4 18 2	80 (by extrapolation)
60		32	400;380;300;300 340; 340; 380	350	290 320 340	7 5 3	260 (by extrapolation)
62	Residues Cell 5	43.5	110; 60; 90	90	60 90 110	18 1 1	Less than 60
63		36	230; 110; 140 140; 110	150	170 110 60 80	1 2 >30 25	80
64	Kent	36.5	200; 170; 200	190	140 170 170 (After Nil at 110 & 140)	>30 <1 <1	170
65		32.5	230 ; 200	220	200 200 (After Nil at 170)	3 9	200

Table 12 (Cont'd)

Run No.	Oil	Temp. °F	Yield Value using AFLAC Method (stress increased every 5 minutes)		Yield Value using Constant Shear Stresses for up to 30 minutes		
			Individual Results dynes/cm^2	Mean dynes/cm^2	Shear Stress dynes/cm^2	Time to Movement (mins)	Yield Value dynes/cm^2
67	F.21	36.5	390; 420; 420	410	340 (After Nil at 280 and 310) 360 (After Nil at 340) 390 (After Nil at 360)	21 28 12	340
68		36.5 (Only 3 days storage)	430 day before run Less than 460 day after run	About 460	310 (After Nil at 280) Both on day before run 370 400 (After Nil at 340 and 370) Both on day after run	8 20 <1	340
70		50	110; 140	130	110 110 (After Nil at 80)	2 1	110
No run*	Curacao	32	-	-	110 140 170	7; 12 2 1	90 (by extrapolation)

* 8 days storage in yield value tubes.

TABLE 13

Results Obtained with C.R.C. Tubes

Oil	Run No.	Temp. °F	Pressure at which oil moved "Hg	Pressures applied for 5 mins. each at which oil did not yield. "Hg	Conditions after oil moved			Yield Value	
					Rate of Shear sec^{-1}	Shear Stress dynes/cm^2	Viscosity poise	Direct Measurement dynes/cm^2	From Rheograms dynes/cm^2
F.36	46	48	3½	-	0.55	150	280	Well below 150	-
			3½	-	0.81	150	190		
			3½	-	0.50	150	300		
.36	47	36	6	-	0.15	300	2000	Less than 300	200 to 250
			8	-	0.35	410	1200		
			9½	-	0.89	500	560		
	48	36	8	-	0.27	410	1500	Less than 400	200 to 250
			9½	-	0.41	500	1220		
			10½	-	0.44	560	1270		
	51	36	6	-	0.24	300	1250	Less than 300	200 to 250
			7	-	0.46	350	780		
	54	37	5	3; 4	0.042	240	5700	240	200 to 250
			6	-	0.33	300	900		
			8	-	0.06	410	6900		
			9½	-	0.37	520	1400		
Bahrein	55	47.5	3	-	0.36	125	350	Well below 125	90
			3	-	0.36	125	350		
			4	-	0.66	180	270		
			6	-	2.84	300	105		
	56	36	7	3; 4; 5; 6	0.155	350	2300	330	250
			6	-	0.14	300	2100		
			6	3; 4; 5	0.065	300	4600		
			9	-	0.34	470	1400		
	57	37	7	3; 4; 5; 6	0.085	350	4200	355	280
			6	-	0.069	300	4500		
			7	3; 4; 5; 6	0.094	350	3800		
			9	-	0.25	470	1800		
Cell 5 Residues	63	36	4	3	0.078	180	2300	180	About 140
			4	3	0.087	180	2100		
			6	-	0.083	300	3600		
			8	-	0.23	410	1800		
Kent	64	36.5	6	-	0.36	300	830	180	About 120
			4	3	0.13	180	1400		
	65	32.5	6	-	0.22	300	1400	Less than 300	-
	66	32.5	6	-	0.20	300	1500	Less than 240	220
			8	-	0.33	410	1200		
			5	-	0.064	240	3800		
F.21	67	36.5	8	3;4;5;6;7	0.029	410	14000	410	-
			8	3;4;5;6;7	0.030	410	13700		
	68	36.5	10	3;4;5;6;7;8;9	0.030	530	17500	525	-
			10	9	0.035	530	1500		
	70	50	3	-	0.17	125	730	Well below 125	-
			3	-	0.18	125	690		
			3	-	0.37	125	340		
					(Temp. 2°F high)				

TABLE 14

Comparison of Yield Value with Behaviour of Oils in Pipe

Run No.	Oil	Temp. °F	Yield Value deduced from: Constant Shear Stress Viscometer dynes/cm²	Yield Value deduced from: AFLAC Narrow bore tubes: AFLAC Method Stress increased every 5 mins. dynes/cm²	Yield Value deduced from: AFLAC Narrow bore tubes: Stress increased every 30 mins. dynes/cm²	Yield Value deduced from: CRC tubes: Direct Measurement Stress increased every 5 mins. dynes/cm²	Yield Value deduced from: CRC tubes: From Rheogram dynes/cm²	Rate of Flow in Pipe: Shear Stress dynes/cm²	Rate of Flow in Pipe: Time to reach flow rate of: Continuous Flow mins.	Rate of Flow in Pipe: Time to reach flow rate of: 0.1 gpm mins.	Rate of Flow in Pipe: Time to reach flow rate of: 0.5 gpm mins.
46	F.36	48	-	70	60	Well below 150	-	145	<1	<1	1
47		36	About 325	190	140	<300	200 to 250	Initially nearly 600 (Line clearing run)	-	Less than 15 mins. No other details owing to air leak.	
48		36	Well below 400	220	-	<400	200 to 250	Initially 575 (Line clearing)	-	(Unreliable owing to air leak)	50
51		36	290	210	140	<300	200 to 250	290	2	5	25
54		37	Less than 300	320	-	240	200 to 250	315	-	120	-
55	Bahrein	47.6	Well below 100	60	-	Well below 125	90	175	<1	1	4
56		36	Less than 150	280	<170	330	250	315	4	15	34
57		37	About 175	310	230	350	280	320	40	70	117
59		38	Less than 150	150	80	-	-	320 (Line clearing)	5	6	8
60		32.5	About 275	350	260	-	-	330 (Line clearing)	24	46	63
62	Cell 5 Residues	43.5	Less than 100	90	<60	-	-	110	50	80	208
63		36	About 150	150	80	180	About 140	280	55	55	60
64	Kent	36	Well below 200	190	170	180	About 120	285	12	18	31
65		32.5	Less than 200	215	200	<300	-	280 (Line clearing)	9	10	17
66		32.5	About 200	-	-	<240	220	285	30	58	95
67	F.21	36	About 500	410	340	410	-	Initially 490 (Line clearing)	-	-	410
68		36.5	Between 300 and 500	About 460	340	530	-	Initially 455 (Line clearing)	-	95	214
70		50	Less than 200	130	110	Well below 125	-	310	60	175	285

TABLE 15

Comparison of CRC and Pipe Viscosities

Viscosities are calculated for both when the oil has moved along the pipe for a distance equal to six to twelve pipe diameters.

Oil	Run No.	Temp. °F	CRC Tube		Pipe	
			Shear Stress dynes/cm^2	Viscosity Poise	Shear Stress dynes/cm^2	Viscosity poise
F.36	46	48	150 150 150	280 190 300	145	140
Bahrein	55	47.5	180	270	175	350
	56	36	300 300 350	4600 2100 2300	315	3000
	57	37	300 350 350	4500 4200 3800	320	4800
Kent	64	36.5	300	830	285	1400
	65	32.5	300	1400	280	1900
	66	32.5	300	1500	285	4200
F.21	68	36.5	530 530	17500 15000	455	19000

TABLE 16

Pipe Viscosities Under Steady Flow Conditions Compared with Laboratory Viscosities

<table>
<tr><th rowspan="3">Run No.</th><th rowspan="3">Temp. °F</th><th rowspan="3">Oil</th><th colspan="3">Conditions at Steady Flow</th><th colspan="6">Viscosities determined in Co-axial Cylinder Viscometers</th></tr>
<tr><th rowspan="2">Rate of Shear sec^{-1}</th><th rowspan="2">Residence Time Mins.</th><th rowspan="2">Pipe Viscosity Poise</th><th colspan="2">At ½ Residence Time</th><th colspan="2">At Residence Time</th><th colspan="2">"Equilibrium"</th></tr>
<tr><th>Oil in Beakers Poise</th><th>Oil in Tank Poise</th><th>Oil in Beakers Poise</th><th>Oil in Tank Poise</th><th>Oil in Beakers Poise</th><th>Oil in Tank Poise</th></tr>
<tr><td>46</td><td>48</td><td rowspan="7">F.36</td><td>6.9</td><td>7</td><td>21</td><td>19</td><td>-</td><td>17</td><td>-</td><td>14</td><td>-</td></tr>
<tr><td>46</td><td>48</td><td>About 26</td><td>2</td><td>About 11</td><td>13</td><td>-</td><td>12</td><td>-</td><td>10</td><td>-</td></tr>
<tr><td>51</td><td>36</td><td>2.4</td><td>22</td><td>120</td><td>120</td><td>-</td><td>105</td><td>-</td><td>75</td><td>-</td></tr>
<tr><td>51</td><td>36</td><td>4.9</td><td>11</td><td>79</td><td>95</td><td>-</td><td>79</td><td>-</td><td>50</td><td>-</td></tr>
<tr><td>53</td><td>48</td><td>4.4</td><td>12</td><td>43</td><td>-</td><td>48</td><td>-</td><td>43</td><td>-</td><td>33</td></tr>
<tr><td>54</td><td>37</td><td>3.7</td><td>14</td><td>111</td><td>115</td><td>95</td><td>96</td><td>82</td><td colspan="2">56</td></tr>
<tr><td>54</td><td>37</td><td>1.9</td><td>28</td><td>171</td><td>180</td><td>150</td><td>140</td><td>125</td><td colspan="2">100</td></tr>
<tr><td>55</td><td>47.5</td><td rowspan="6">Bahrein</td><td>3.9</td><td>14</td><td>45</td><td colspan="2">42</td><td colspan="2">39</td><td colspan="2">30</td></tr>
<tr><td>55</td><td>47.5</td><td>11.8</td><td>4½</td><td>27</td><td colspan="2">28</td><td colspan="2">25</td><td colspan="2">20</td></tr>
<tr><td>56</td><td>36</td><td>2.9</td><td>18</td><td>110</td><td>150</td><td>86</td><td>130</td><td>70</td><td>85</td><td>60</td></tr>
<tr><td>56</td><td>36</td><td>4.8</td><td>11</td><td>81</td><td>115</td><td>75</td><td>100</td><td>65</td><td>62</td><td>48</td></tr>
<tr><td>57</td><td>37</td><td>1.65</td><td>32</td><td>194</td><td colspan="2">180</td><td colspan="2">155</td><td colspan="2">120</td></tr>
<tr><td>57</td><td>37</td><td>2.8</td><td>19</td><td>141</td><td colspan="2">125</td><td colspan="2">110</td><td colspan="2">75</td></tr>
<tr><td>62</td><td>43.5</td><td rowspan="4">Cell 5</td><td>1.0</td><td>51</td><td>111</td><td>145</td><td>90</td><td>135</td><td>75</td><td>125</td><td>70</td></tr>
<tr><td>62</td><td>43.5</td><td>7.7</td><td>7</td><td>40</td><td>46</td><td>34</td><td>44</td><td>30</td><td>32</td><td>25</td></tr>
<tr><td>63</td><td>36</td><td>1.3</td><td>40</td><td>216</td><td>270</td><td>225</td><td>225</td><td>195</td><td>200</td><td>170</td></tr>
<tr><td>63</td><td>36</td><td>2.7</td><td>19</td><td>142</td><td>150</td><td>135</td><td>130</td><td>120</td><td>95</td><td>85</td></tr>
<tr><td>64</td><td>36.5</td><td rowspan="2">Kent</td><td>3.0</td><td>17</td><td>95</td><td>90</td><td>-</td><td>78</td><td>-</td><td>45</td><td>-</td></tr>
<tr><td>66</td><td>32.5</td><td>2.0*</td><td>26</td><td>150</td><td colspan="2">135</td><td colspan="2">120</td><td colspan="2">80</td></tr>
</table>

* Flow rate still increasing slowly at this stage and tank nearly empty.

TABLE 17

Viscosities and Shear Stresses at Times of Shearing Equal to Half Mean Residence Times of the Oils in the Pipe

Oil	Run No.	Temp. °F	Time of storage days	Beakers in Cold Room: Rate of Shear sec^{-1}	Beakers in Cold Room: Shear Stress $dynes/cm^2$	Beakers in Cold Room: Viscosity Poise	Tank: Position	Tank: Rate of Shear sec^{-1}	Tank: Shear Stress $dynes/cm^2$	Tank: V
F.36	46	48	25	1.63 6.8 9.7 18.8	47 155 : 121 141 258	 23 : 18 14.5 13.7	-	-	-	
	47	36	9	1.8 3.6 9.1	240 345 455	133 96 50	-	-	-	
	48	36	7	0.79 9.1	197 455	250 50	-	-	-	
	51	36	16	0.79 1.8 4.9 9.1	215 230 470 575	272 140 96 63	-	-	-	
	53	48	21 in all including an unintentional reheat to 66°F				Residue after run Top " " " Top " " " Residue after run	2.4 3.5 6.7 9.7	185 213 : 189 255 : 241 291	
	54	37	23	1.8 3.3 4.9 9.1	330 425 450 637	183 129 92 70	Top Centre Top Top : Centre	0.79 1.8 3.3 4.9	195 306 360 396 : 376	
Bahrein	55	47.5	21	1.6 2.4 6.7 9.7	86 122 195 280	54 51 29 29	Top Centre Top Top : Centre	1.6 3.5 6.7 9.7	98 179 234 310 : 262	
	56	36	24	0.43 1.8 3.3 4.9	177 360 442 525 : 570	410 200 134 107 : 116	Top* Top*: Centre Centre Top*	1.8 3.3 4.9 9.1	175 244 : 291 382 565	
	57	37	49	1.3 1.8 3.3 4.9 9.1	280 333 356 475 730	215 185 108 97 80	Bottom Top : Centre Top : Centre Top : Bottom	1.3 1.8 3.3 4.9	359 333 : 326 366 : 386 461 : 466	
	59	40≠	8	1.8:3.3:9.1	257:422:655	143:128:72	-	-	-	
	60	32.5	7	1.3:3.3:9.1	351:597:875	270:181:96	-	-	-	
Residues from Cell 5 Rosyth	62	43.5	30 5 at test temp. after slow cooling	1.6 3.3 4.8 9.1	162 231 280 400	101 70 57 44	Centre Bottom Centre	1.1 3.3 9.1	88 171 273	
	63	36	21	1.3 1.8 3.3 9.1	358 330 455 745	275 183 138 82	Bottom Centre Centre Bottom	1.3 1.8 3.6 9.1	293 267 460 645	
Curacao	-	36	18	1.3 4.9 9.1	296 490 690	227 100 76	-	-	-	
	-	32	8	1.3 4.9 9.1	366 660 830	282 135 91	-	-	-	
Kent	64	36.5	26	1.3 1.8 4.9 9.1	212 236 348 455	163 131 71 50	- Top	- 4.9	- 324	
	65	32.5	22 14 at test temperature	1.8 2.4 4.9 9.1	320 322 416 610	178 134 85 67	-	-	-	
	66	32.5	21	1.8 4.9 9.1	266 382 528	148 78 58	Centre ? Centre ?	2.4 4.9	298 411	
F.21	70	50	29	1.8 3.3 9.1	261 372 582	145 116 } 49°F 64	Centre Centre Centre	1.3 1.8 3.3	159 213 280	12 11 8

≠ Beakers warmer than pipe.
* Thin crust on top breaks readily as sample is taken.

TABLE 17

Shear Stresses at Times of Shearing Equal to Half Mean Residence Times of the Oils in the Pipe

Time of storage days	Beakers in Cold Room			Tank			
	Rate of Shear sec^{-1}	Shear Stress $dynes/cm^2$	Viscosity Poise	Position	Rate of Shear sec^{-1}	Shear Stress $dynes/cm^2$	Viscosity Poise
25	1.63	47		-	-	-	-
	6.8	155 : 121	23 : 18				
	9.7	141	14.5				
	18.8	258	13.7				
9	1.8	240	133	-	-	-	-
	3.6	345	96				
	9.1	455	50				
7	0.79	197	250	-	-	-	-
	9.1	455	50				
16	0.79	215	272	-	-	-	-
	1.8	230	140				
	4.9	470	96				
	9.1	575	63				
21 in all including an unintentional reheat to 66°F				Residue after run	2.4	185	77
				Top " " "	3.5	213 : 189	61 : 54
				Top " " "	6.7	255 : 241	38 : 36
				Residue after run	9.7	291	30
23	1.8	330	183	Top	0.79	195	247
	3.3	425	129	Centre	1.8	306	170
	4.9	450	92	Top	3.3	360	109
	9.1	637	70	Top : Centre	4.9	396 : 376	81 : 77
21	1.6	86	54	Top	1.6	98	61
	2.4	122	51	Centre	3.5	179	51
	6.7	195	29	Top	6.7	234	35
	9.7	280	29	Top : Centre	9.7	310 : 262	32 : 27
24	0.43	177	410	Top*	1.8	175	97
	1.8	360	200	Top*: Centre	3.3	244 : 291	74 : 88
	3.3	442	134	Centre	4.9	382	78
	4.9	525 : 570	107 : 116	Top*	9.1	565	62
49	1.3	280	215	Bottom	1.3	359	276
	1.8	333	185	Top : Centre	1.8	333 : 326	185 : 181
	3.3	356	108	Top : Centre	3.3	366 : 386	111 : 117
	4.9	475	97	Top : Bottom	4.9	461 : 466	94 : 95
	9.1	730	80				
8	1.8:3.3:9.1	257:422:655	143:128:72	-	-	-	-
7	1.3:3.3:9.1	351:597:875	270:181:96	-	-	-	-
30	1.6	162	101	Centre	1.1	88	80
5 at test tmp.≠	3.3	231	70	Bottom	3.3	171	52
after slow	4.8	280	57				
cooling	9.1	400	44	Centre	9.1	273	30
21	1.3	358	275	Bottom	1.3	293	225
	1.8	330	183	Centre	1.8	267	148
	3.3	455	138	Centre	3.6	460	128
	9.1	745	82	Bottom	9.1	645	71
18	1.3	296	227	-	-	-	-
	4.9	490	100				
	9.1	690	76				
8	1.3	366	282	-	-	-	-
	4.9	660	135				
	9.1	830	91				
26	1.3	212	163	-	-	-	-
	1.8	236	131				
	4.9	348	71	Top	4.9	324	64
	9.1	455	50				
22	1.8	320	178	-	-	-	-
14 at test	2.4	322	134				
temperature	4.9	416	85				
	9.1	610	67				
21	1.8	266	148	Centre ?	2.4	298	124
	4.9	382	78	Centre ?	4.9	411	84
	9.1	528	58				
29	1.8	261	145	Centre	1.3	159	122
	3.3	372	116 } 49°F	Centre	1.8	213	118 } 51°F
	9.1	582	64	Centre	3.3	280	85

≠ Beakers warmer than pipe.

* Thin crust on top breaks readily as sample is taken.

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TABLE 18

Flow Rates Calculated from Viscosity Data in Table 17 Compared with those obtained in the Pipe

Oil	Run No.	Temp. °F	Time of Storage days	Shear Stress dynes/cm²	Rate of Shear sec⁻¹ From Beakers	Rate of Shear sec⁻¹ From Tank	Rate of Shear sec⁻¹ Obtained in Pipe	Flow Rate g.p.m. From Beakers	Flow Rate g.p.m. From Tank	Flow Rate g.p.m. Obtained in Pipe	
F.36	46	48	25	145	8.5	-	6.9	11.5	-	9.4	
				300	22.5	-	About 26	30	-	About 36	
				400	32	-	-	43	-	-	
	47 & 48	36	9 and 7	300	3.3	-	-	4.5	-	-	No
				400	6.2	-	-	8.4	-	-	c
	51	36	16	280	2.3	-	2.4	3.1	-	3.2	
				300	2.6	-	-	3.5	-	-	
				390	4.4	-	4.9	6.0	-	6.6	
				400	4.6	-	-	6.2	-	-	
	53	48	21	190	-	2.9	4.4	-	3.9	6.0	Ta
			Including repeat	300	-	10.0	-	-	13.5	-	l
			to 60°F	400	-	16	-	-	22	-	v
	54	37	23	300	1.0	2.4	-	1.3	3.2	-	
				325	1.6	2.9	1.9	2.2	3.9	2.6	
				400	3.2	4.6	-	4.3	6.2	-	
				415	3.5	5.0	3.7	4.7	6.8	5.0	
Bahrein	55	47.5	21	175	4.6	4.6	3.9	6.2	6.2	5.2	Oi
				300	10.3	10.3	-	13.9	13.9	-	s
				315	10.9	10.9	11.8	14.7	14.7	15.9	
				400	15	15	-	20	20	-	
	56	36	24	300	1.5	3.8	-	2.0	5.1	-	
				315	1.6	4.1	2.9	2.2	5.5	3.6	
				390	2.5	5.4	4.8	3.3	7.3	6.5	
				400	2.6	5.6	-	3.5	7.6	-	
	57	37	49	300	1.5	1.5	-	2.0	2.0	-	Oil
				320	1.9	1.9	1.7	2.6	2.6	2.2	si
				395	3.3	3.3	2.8	4.5	4.5	3.8	
				400	3.4	3.4	-	4.6	4.6	-	
	59	40	8	300	2.0	-	-	2.7	-	-	No
				400	3.1	-	-	4.2	-	-	cl
	60	32.5	7	300	0.6	-	-	0.8	-	-	No
				400	1.5	-	-	2.0	-	-	cl
Residue from Cell 5 Rosyth	62	43.5	30 in all	115	0.5	1.7	1.0	0.7	2.3	1.4	
			5 at test	300	5.5	10.5	-	7.4	14.2	-	
			temp.	305	5.6	11.0	7.6	7.6	14.9	10.4	
				400	9.1	About 78	-	12.3	About 24	-	
	63	36	21	280	0.7	1.6	1.3	0.9	2.0	1.8	
				300	0.9	1.7	-	1.2	2.3	-	
				370	1.8	2.8	2.7	2.4	3.8	3.6	
				400	2.2	3.2	-	3.0	4.3	-	
Curacao	-	36	18	300	1.4	-	-	1.9	-	-	Ins
				400	3.2	-	-	4.3	-	-	th
	-	32	8	300	0.5	-	-	0.7	-	-	Ins
				400	1.6	-	-	2.2	-	-	th
Kent	64	36.5	26	285	3.1	-	3.0	4.2	-	4.1	Tan
				300	3.5	-	-	4.7	-	-	an
				400	6.7	-	-	9.1	-	-	co
	65	32.5	22 in all	300	1.7	-	-	2.3	-	-	No
			14 at test temp.	400	4.1	-	-	5.6	-	-	ol
	66	32.5	21	300	2.5	2.5	2.0	3.4	3.4	2.7	Tan
				400	5.0	5.0	-	6.8	6.8	-	co in inc ta
F.21	70	50	29	300	2.2	3.4	-	3.0	4.6	-	Bea
				325	2.7	3.8	-	4.0	5.1	-	ce
				400	4.0	5.5	-	5.4	7.5	-	oil

TABLE 18

Rates Calculated from Viscosity Data in Table 17 Compared with those obtained in the Pipe

Time of storage days	Shear Stress dynes/cm²	Rate of Shear sec⁻¹ From Beakers	Rate of Shear From Tank	Rate of Shear Obtained in Pipe	Flow Rate g.p.m. From Beakers	Flow Rate From Tank	Flow Rate Obtained in Pipe	Remarks
25	145	8.5	-	6.9	11.5	-	9.4	
	300	22.5	-	About 26	30	-	About 36	
	400	32	-	-	43	-	-	
and 7	300	3.3	-	-	4.5	-	-	No pipe data. Line clearing runs.
	400	6.2	-	-	8.4	-	-	
16	280	2.3	-	2.4	3.1	-	3.2	
	300	2.6	-	-	3.5	-	-	
	390	4.4	-	4.9	6.0	-	6.6	
	400	4.6	-	-	6.2	-	-	
21 ding repeat 60°F	190	-	2.9	4.4	-	3.9	6.0	Tank viscosities all on top layers probably more viscous than centre.
	300	-	10.0	-	-	13.5	-	
	400	-	16	-	-	22	-	
23	300	1.0	2.4	-	1.3	3.2	-	
	325	1.6	2.9	1.9	2.2	3.9	2.6	
	400	3.2	4.6	-	4.3	6.2	-	
	415	3.5	5.0	3.7	4.7	6.8	5.0	
21	175	4.6	4.6	3.9	6.2	6.2	5.2	Oil in beakers and tank in similar condition.
	300	10.3	10.3	-	13.9	13.9	-	
	315	10.9	10.9	11.8	14.7	14.7	15.9	
	400	15	15	-	20	20	-	
24	300	1.5	3.8	-	2.0	5.1	-	
	315	1.6	4.1	2.9	2.2	5.5	3.6	
	390	2.5	5.4	4.8	3.3	7.3	6.5	
	400	2.6	5.6	-	3.5	7.6	-	
49	300	1.5	1.5	-	2.0	2.0	-	Oil in beakers and tank in similar condition.
	320	1.9	1.9	1.7	2.6	2.6	2.2	
	395	3.3	3.3	2.8	4.5	4.5	3.8	
	400	3.4	3.4	-	4.6	4.6	-	
8	300	2.0	-	-	2.7	-	-	No pipe data. Line clearing run
	400	3.1	-	-	4.2	-	-	
7	300	0.6	-	-	0.8	-	-	No pipe data. Line clearing run
	400	1.5	-	-	2.0	-	-	
in all at test temp.	115	0.5	1.7	1.0	0.7	2.3	1.4	
	300	5.5	10.5	-	7.4	14.2	-	
	305	5.6	11.0	7.6	7.6	14.9	10.4	
	400	9.1	About 78	-	12.3	About 24	-	
21	280	0.7	1.6	1.3	0.9	2.0	1.8	
	300	0.9	1.7	-	1.2	2.3	-	
	370	1.8	2.8	2.7	2.4	3.8	3.6	
	400	2.2	3.2	-	3.0	4.3	-	
18	300	1.4	-	-	1.9	-	-	Insufficient oil to fill the rig.
	400	3.2	-	-	4.3	-	-	
8	300	0.5	-	-	0.7	-	-	Insufficient oil to fill the rig.
	400	1.6	-	-	2.2	-	-	
26	285	3.1	-	3.0	4.2	-	4.1	Tank only partially filled and probably in similar condition to pipe.
	300	3.5	-	-	4.7	-	-	
	400	6.7	-	-	9.1	-	-	
in all test temp.	300	1.7	-	-	2.3	-	-	No pipe data. Line clearing run.
	400	4.1	-	-	5.6	-	-	
21	300	2.5	2.5	2.0	3.4	3.4	2.7	Tank & pipe in similar condition. Flow approaching steady state but still increasing slowly when tank emptied.
	400	5.0	5.0	-	6.8	6.8	-	
29	300	2.2	3.4	-	3.0	4.6	-	Beakers at 49°F. Tank centre at 51°F. Insufficient oil to reach steady state.
	325	2.7	3.8	-	4.0	5.1	-	
	400	4.0	5.5	-	5.4	7.5	-	

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TABLE 19

Probable Pumping Rates under Various Conditions

Oil	Temp. °F	Time of storage days	Relevant Test Run	Difficulty if any in starting up under shear stress of 300 dynes/cm²	Probable Steady Flow rate under Shear Stress of 300 dynes/cm² gpm	Probable Steady Flow rate under Shear Stress of 400 dynes/cm² gpm	
F.36	48	21 to 25	46; 53	None	15 to 35	25 to 45	Probably n since vis in Run 53 pumping r
	36	3	50	May take up to one hour to clear line	-	-	
	36	7 to 9	47; 48	May take an hour or more to clear line	About 5	About 8	Flow rates Centre of
	36	16	51	May take an hour or more to clear line	About 4	About 6	
	37	23	54	Should start but may take several hours to clear line	1 to 3	4 to 6	
	32	2	52	May not be possible to clear line even after several hours pumping.	-	-	
Bahrein	48	21	55	None	About 15	About 20	
	40	8	59	None	About 3	About 4	Flow rates in centre readily.
	36	3	58	None	-	-	
	36	24	56	May take an hour or more to clear line	2 to 5	4 to 8	
	37	49	57	Should start but may take several hours to clear line	About 2	About 4	
	32	2	61	May take an hour to clear the line	-	-	
	32	7	60	May take several hours to clear line	About 1	About 2	Flow rates fr in centre readily.
Residue from Cell 5 Rosyth	44	30 in all only 5 at test temp.	62	None	7 to 14	12 to 24	
	36	21	63	May take two hours to clear line.	1 to 2	3 to 4	
Curacao	36	18	None Laboratory Measurements only	None	About 2	About 4	Flow rates f Oil in centr more readil
	32	8		None	About 1	About 2	
Kent	36	26	64	May take up to one hour to clear line	About 5	About 9	
	32	21	65; 66	May take several hours to clear line	About 3	About 7	
F.21	50	29	70	May take several hours to clear line	3 to 5	5 to 8	
	36	3	68	Will take at least several hours to clear line but may not prove possible to do so.	-	-	
	36	6	69	Will not be possible to clear line.	-	-	

TABLE 19

Probable Pumping Rates under Various Conditions

Relevant Test Run	Difficulty if any in starting up under shear stress of 300 dynes/cm^2	Probable Steady Flow rate under Shear Stress of 300 dynes/cm^2 gpm	Probable Steady Flow rate under Shear Stress of 400 dynes/cm^2 gpm	Remarks
46; 53	None	15 to 35	25 to 45	Probably nearer the higher figure, since viscosity data on top samples in Run 53 gave too low a probable pumping rate.
50	May take up to one hour to clear line	-	-	
47; 48	May take an hour or more to clear line	About 5	About 8	Flow rates from beaker samples. Centre of tank may flow more readily.
51	May take an hour or more to clear line	About 4	About 6	
54	Should start but may take several hours to clear line	1 to 3	4 to 6	
52	May not be possible to clear line even after several hours pumping.	-	-	
55	None	About 15	About 20	
59	None	About 3	About 4	Flow rates from beaker samples. Oil in centre of tank may flow more readily.
58	None	-	-	
56	May take an hour or more to clear line	2 to 5	4 to 8	
57	Should start but may take several hours to clear line	About 2	About 4	
61	May take an hour to clear the line	-	-	
60	May take several hours to clear line	About 1	About 2	Flow rates from beaker samples. Oil in centre of tank may flow more readily.
62	None	7 to 14	12 to 24	
63	May take two hours to clear line.	1 to 2	3 to 4	
Néne Laboratory Measurements only	None	About 2	About 4	Flow rates from beaker samples. Oil in centre of tank may flow more readily.
	None	About 1	About 2	
64	May take up to one hour to clear line	About 5	About 9	
65; 66	May take several hours to clear line	About 3	About 7	
70	May take several hours to clear line	3 to 5	5 to 8	
68	Will take at least several hours to clear line but may not prove possible to do so.	-	-	
69	Will not be possible to clear line.	-	-	

TABLE 20

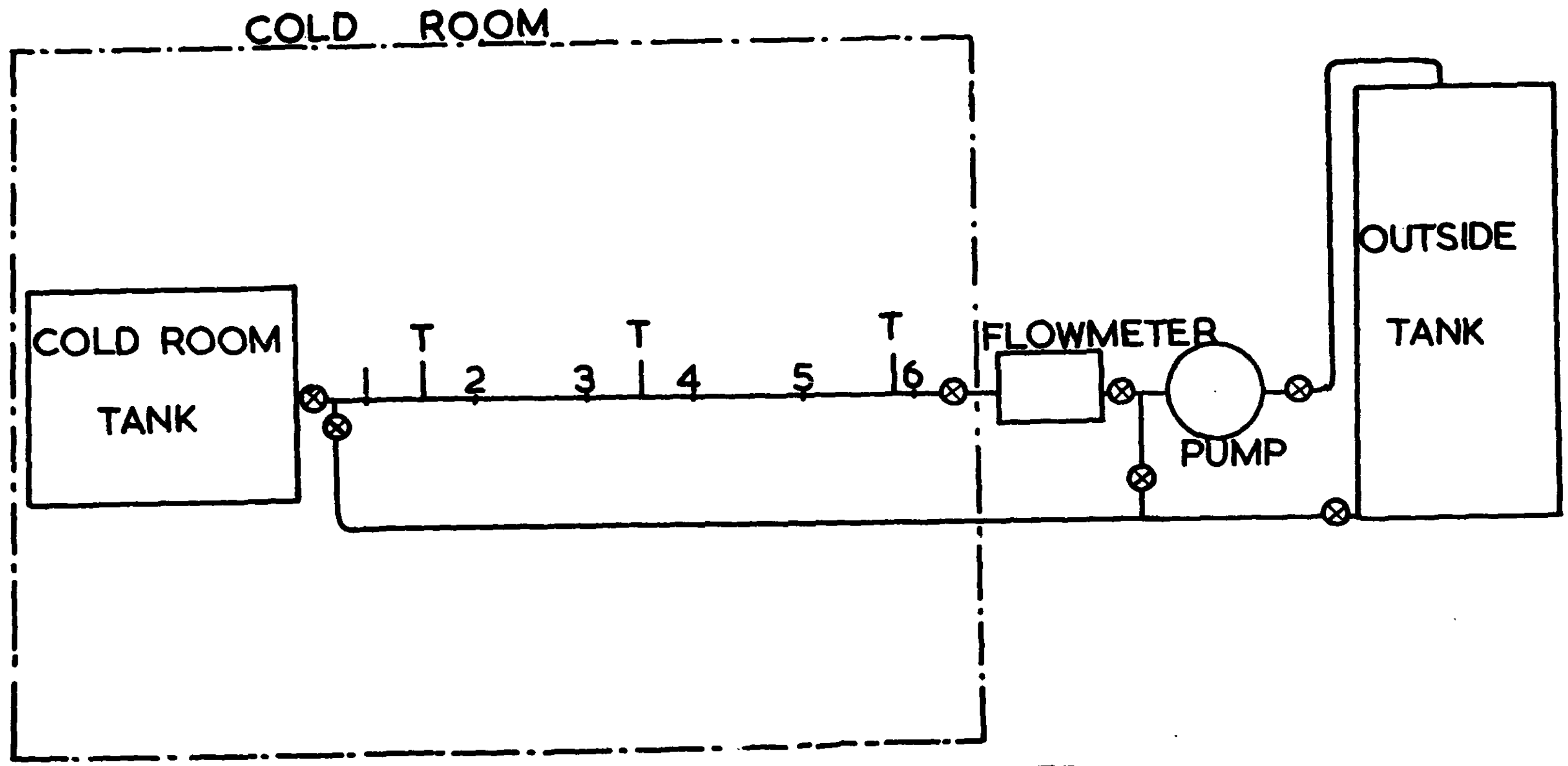
The Variation of Shear Stress and Rate of Shear with the Dimensions of the Pipe

Diameter of Pipe inches	Length of pipe feet	Shear Stress dynes/cm^2 resulting from pressure drop of				Rate of Shear sec^{-1} resulting from flow rate of			
		4 psi	7 psi	10 psi	13 psi	2 g.p.m. ($\frac{1}{2}$ ton/hr)	4 g.p.m. (1 ton/hr)	20 g.p.m. (5 ton/hr)	100 g.p.m. (25 ton/hr)
$3\frac{1}{2}$	20	1000	1760	2520	3270	2.2	4.4	22	110
	30	670	1180	1680	2180				
	50	400	700	1000	1300				
	100	200	350	500	650				
4	30	770	1340	1910	2500	1.5	3.0	14.8	74
	50	460	800	1150	1490				
	100	230	400	580	750				
	150	150	270	380	500				
5	50	580	1010	1440	1870	0.76	1.5	7.6	38
	100	290	500	720	940				
	150	190	330	480	620				
	200	140	250	360	470				
6	50	690	1210	1720	2240	0.44	0.87	4.4	22
	100	350	600	860	1120				
	150	220	380	540	700				
	200	170	300	430	560				

To obtain available pressure drop deduct the pressure loss caused by the difference in level of the pump and the surface of the oil in the tank from the probable maximum suction at the pump. This loss in pressure (in psi) resulting from the oil level being lower than the pump may be regarded as 0.41 x (height in feet of pump above oil surface).

A ton of oil has been taken to be 240 gallons for the purposes of these calculations.

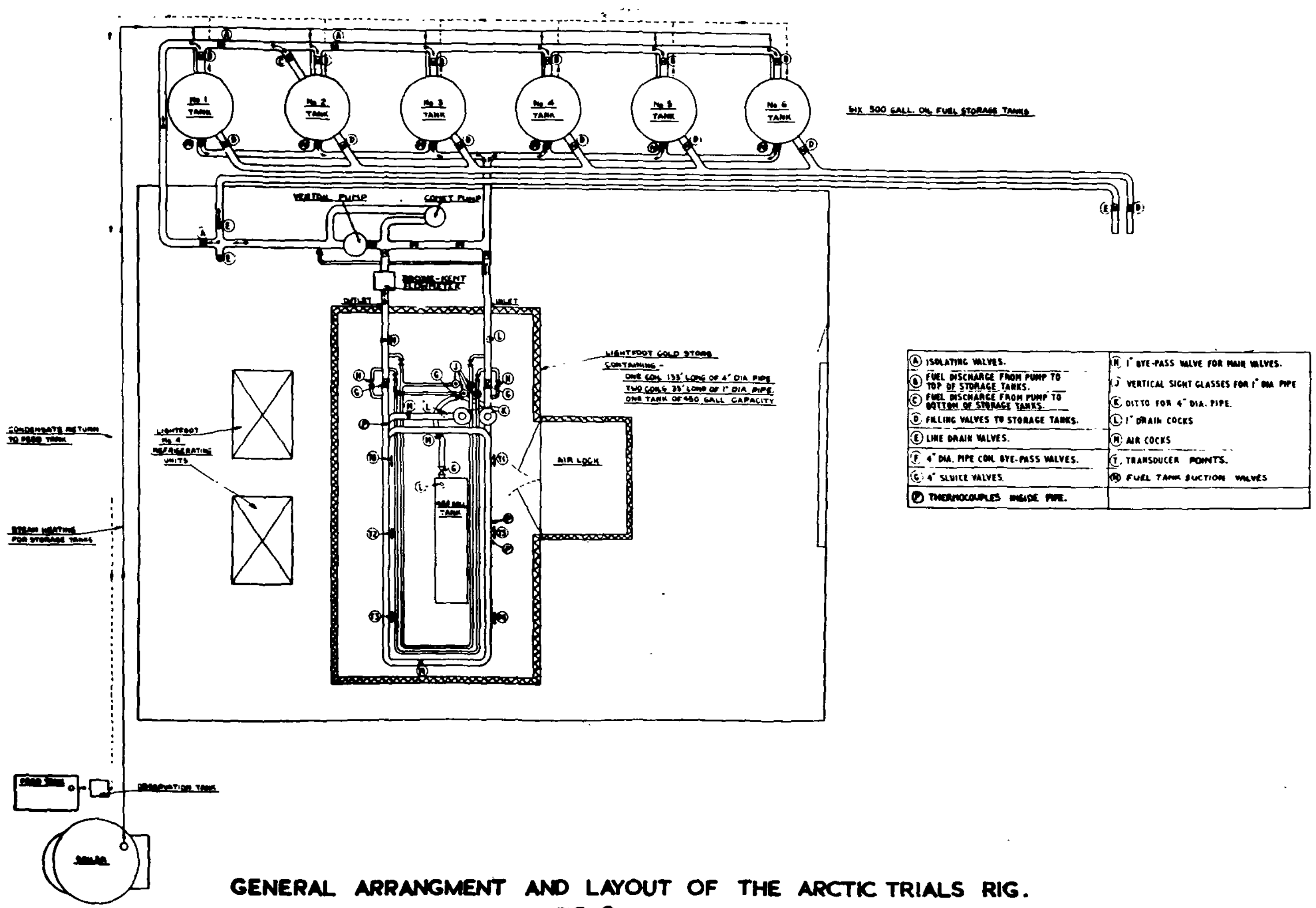
DIAGRAMATIC LAYOUT OF RIG.



PRESSURE TRANSDUCER POINTS NUMBERED.

T — THREE THERMOCOUPLES, ACROSS PIPE.

FIG. 1. DIAGRAMATIC LAYOUT OF THE RIG.



GENERAL ARRANGMENT AND LAYOUT OF THE ARCTIC TRIALS RIG.

FIG. 2.

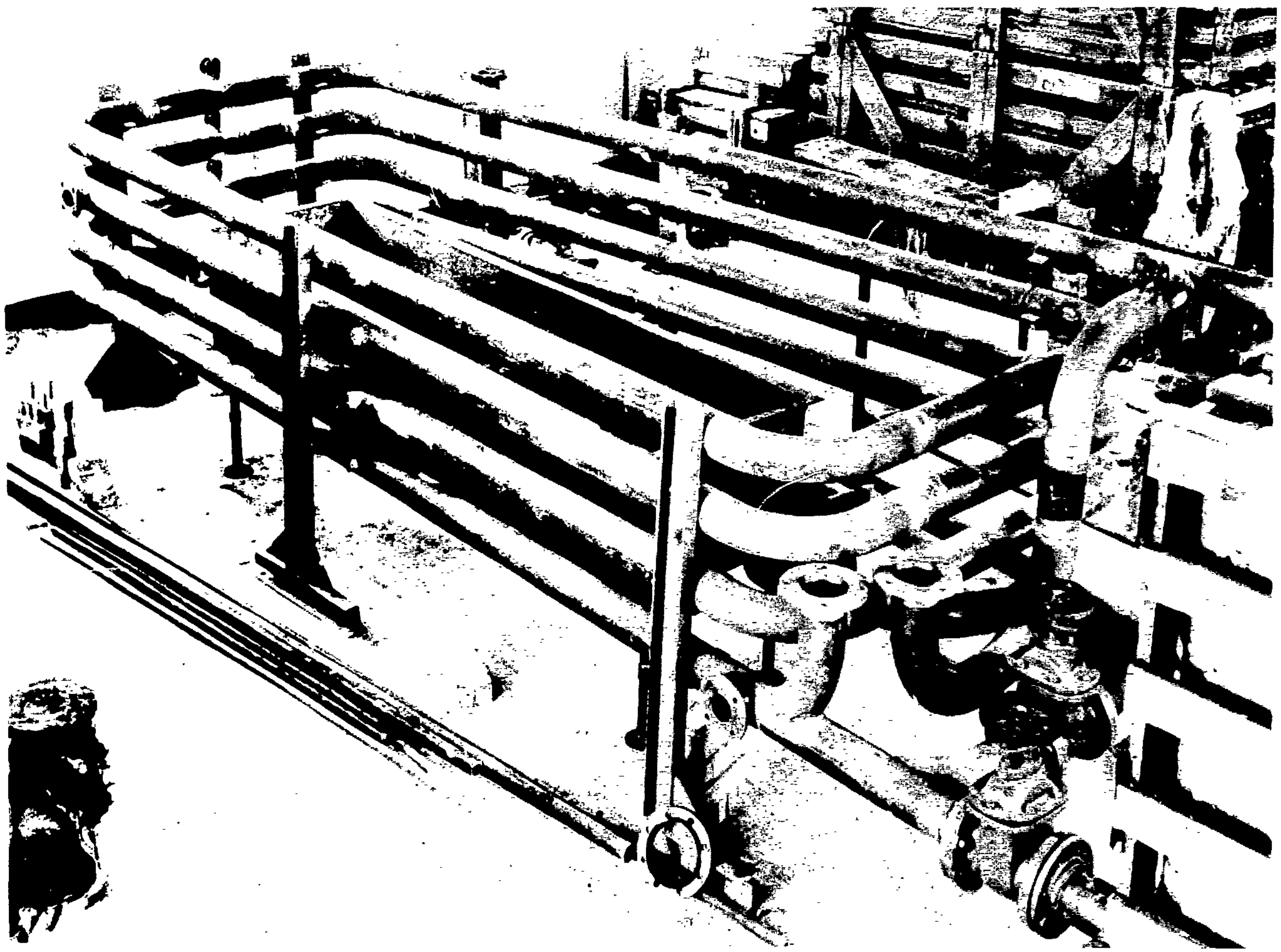


FIG.3. View of Coil before Construction of Cold Room

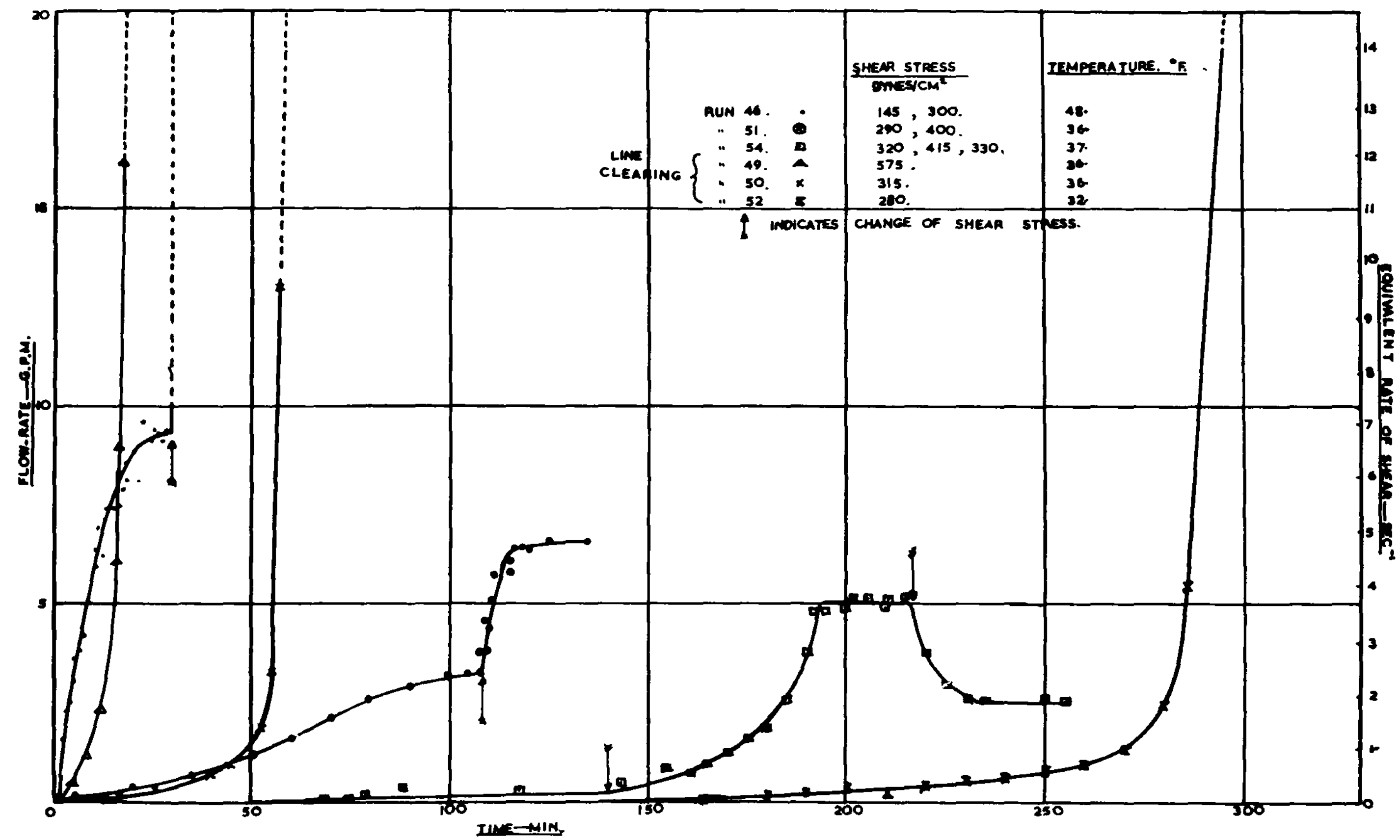


FIG. 4. FLOW RATE FOR RUNS WITH F.36.

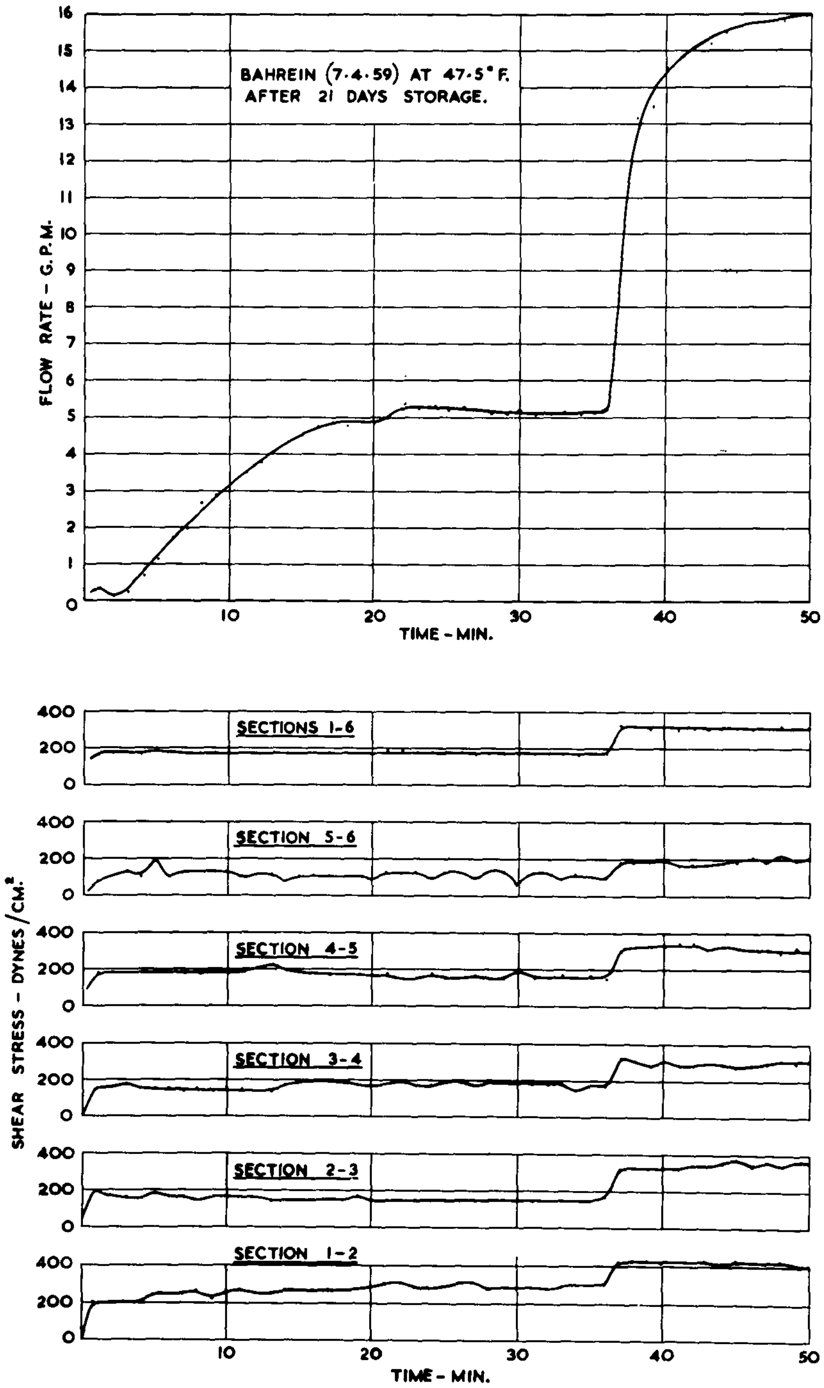


FIG. 5. FLOW RATE & SHEAR STRESSES FOR RUN 55.

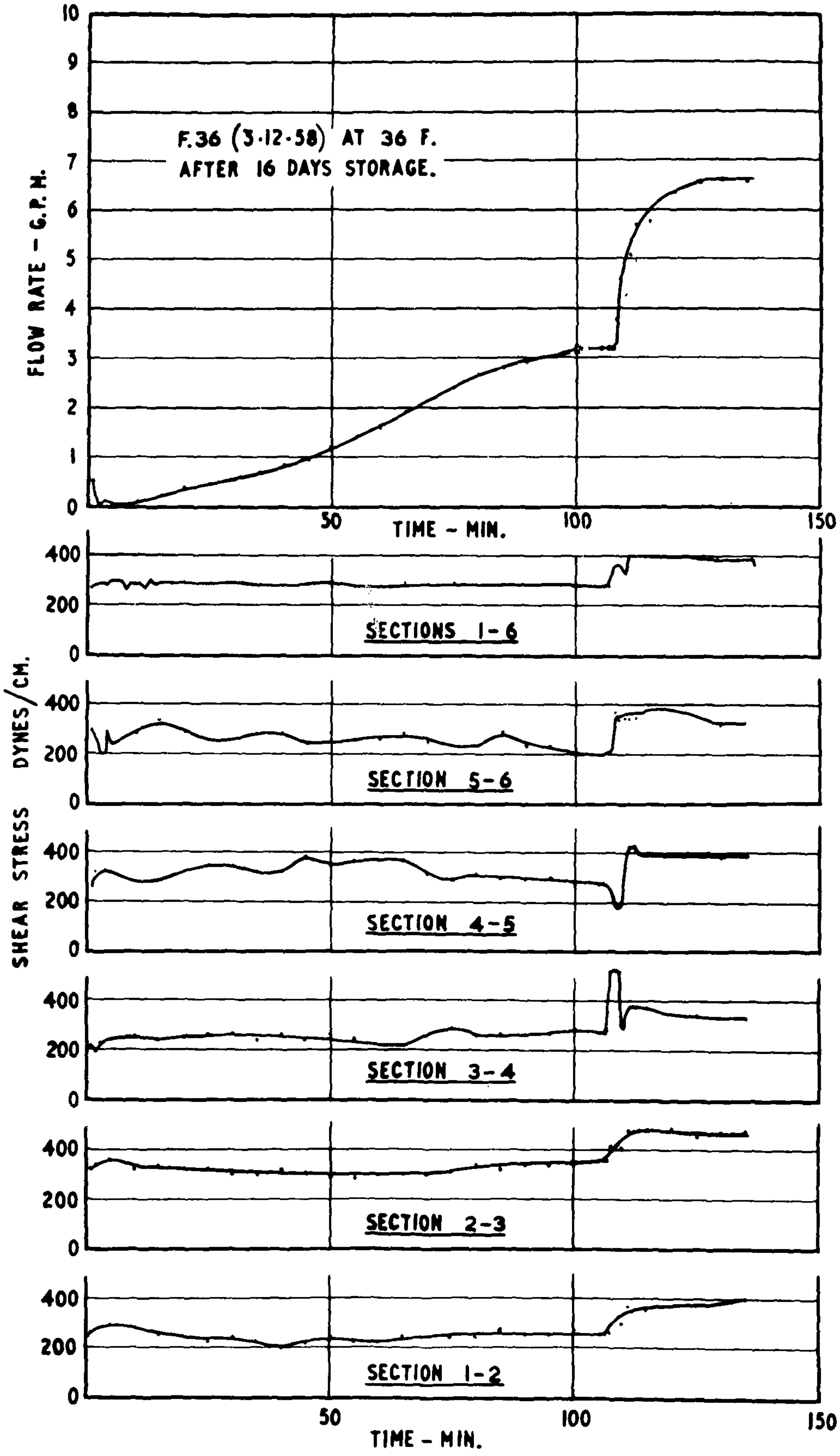


FIG. 6. FLOW RATE & SHEAR STRESSES FOR RUN 51.

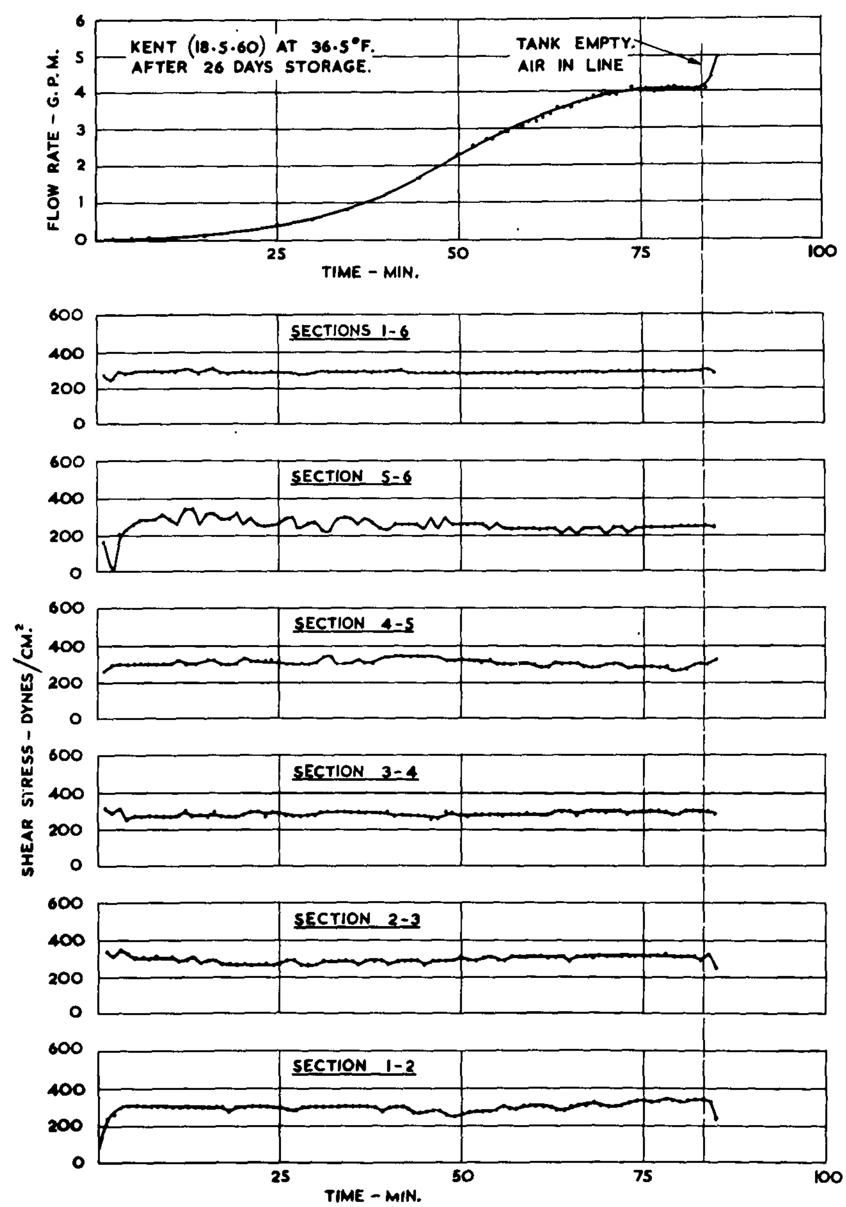


FIG. 7. FLOW RATE & SHEAR STRESSES FOR RUN 64.

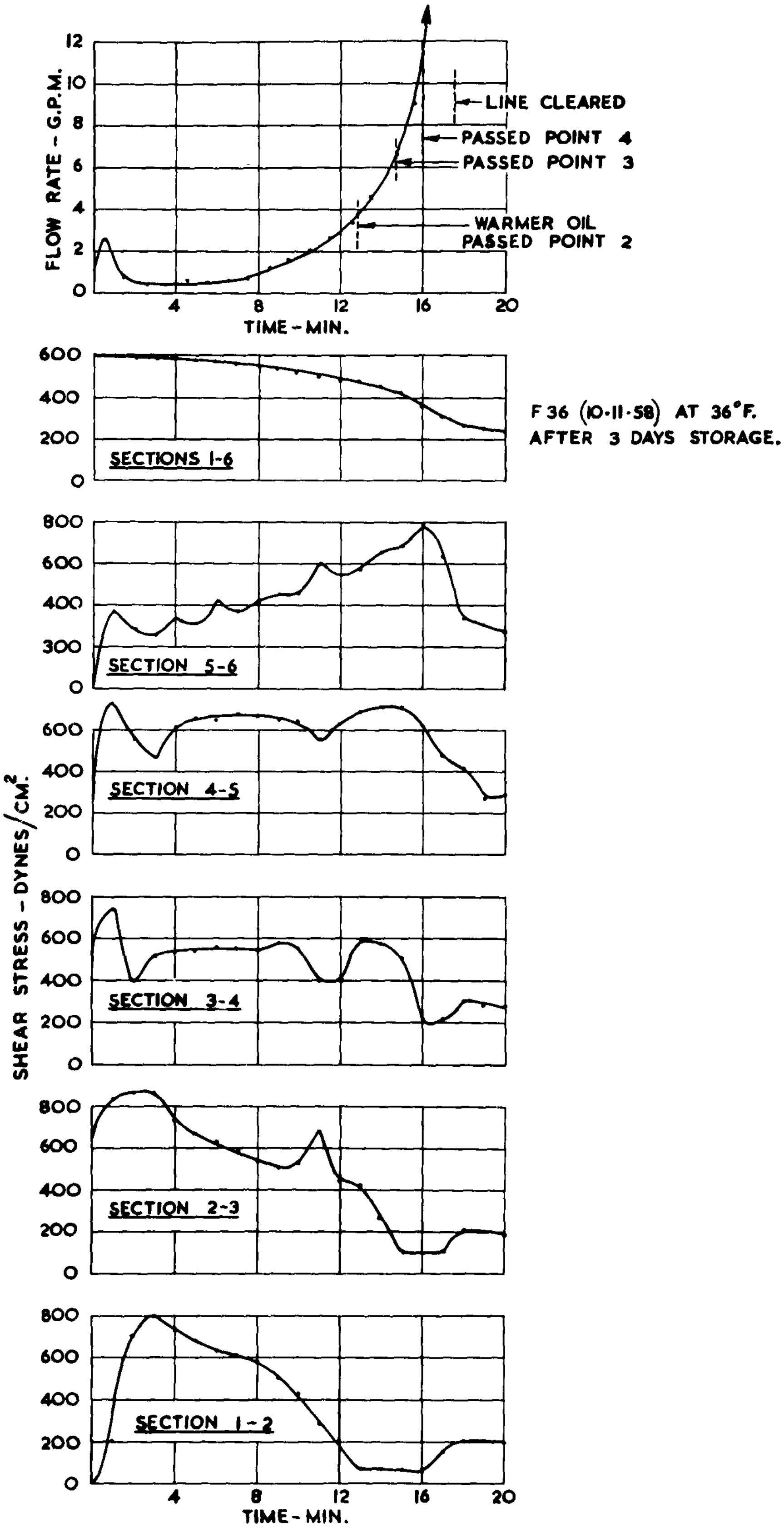


FIG. 8. FLOW RATE & SHEAR STRESSES FOR RUN 49.

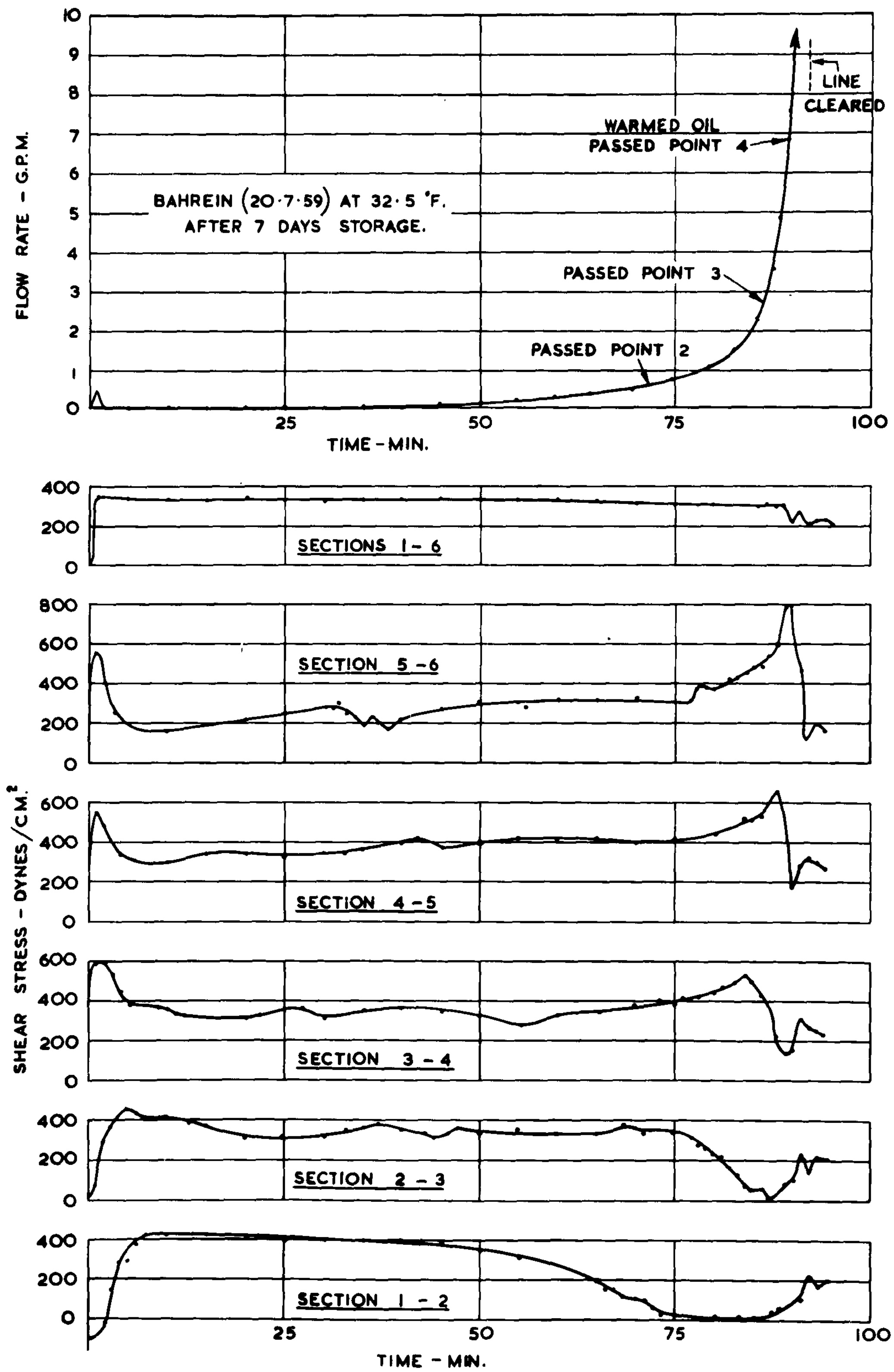


FIG. 9. FLOW RATE & SHEAR STRESSES FOR RUN 60.

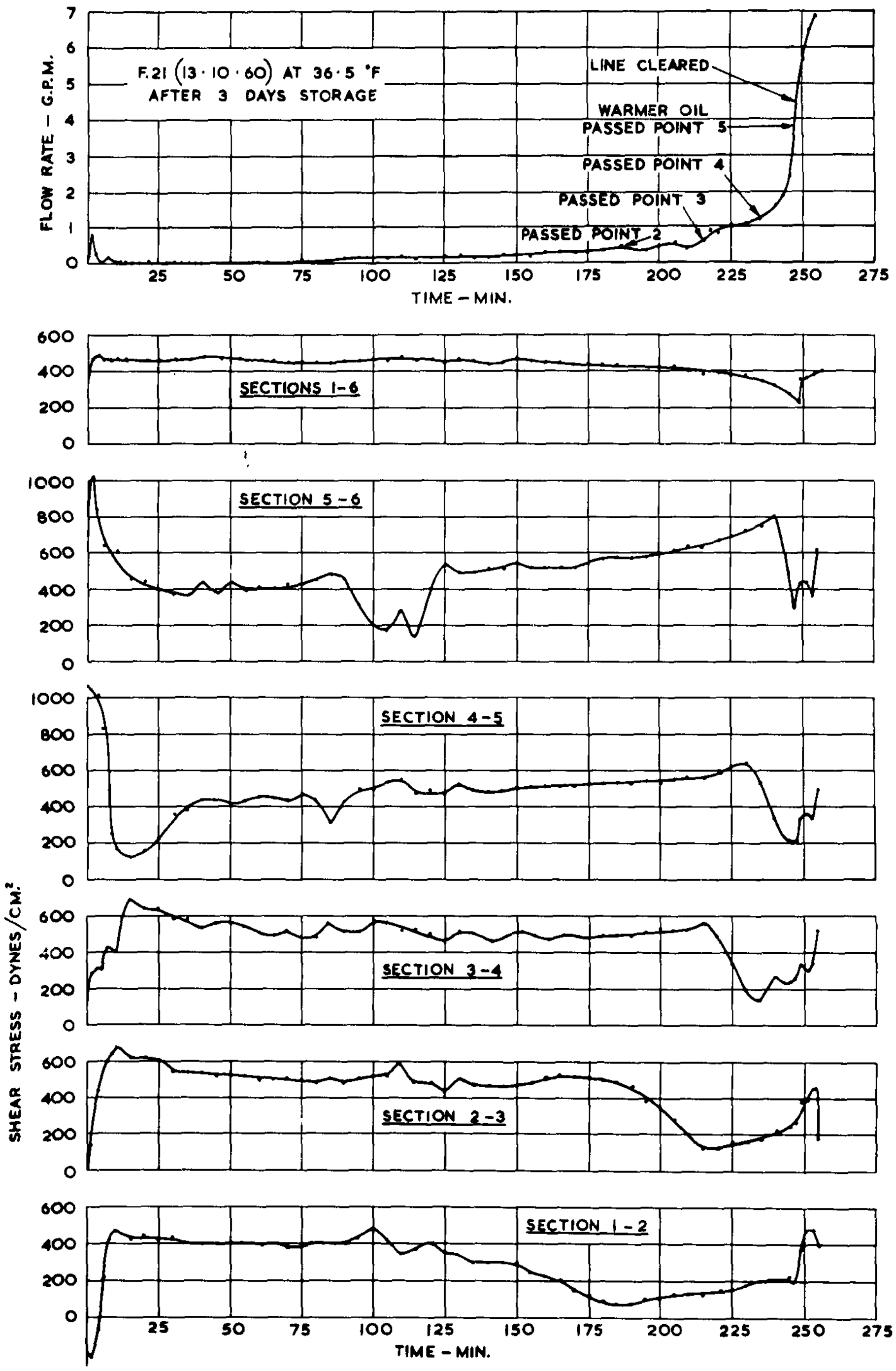
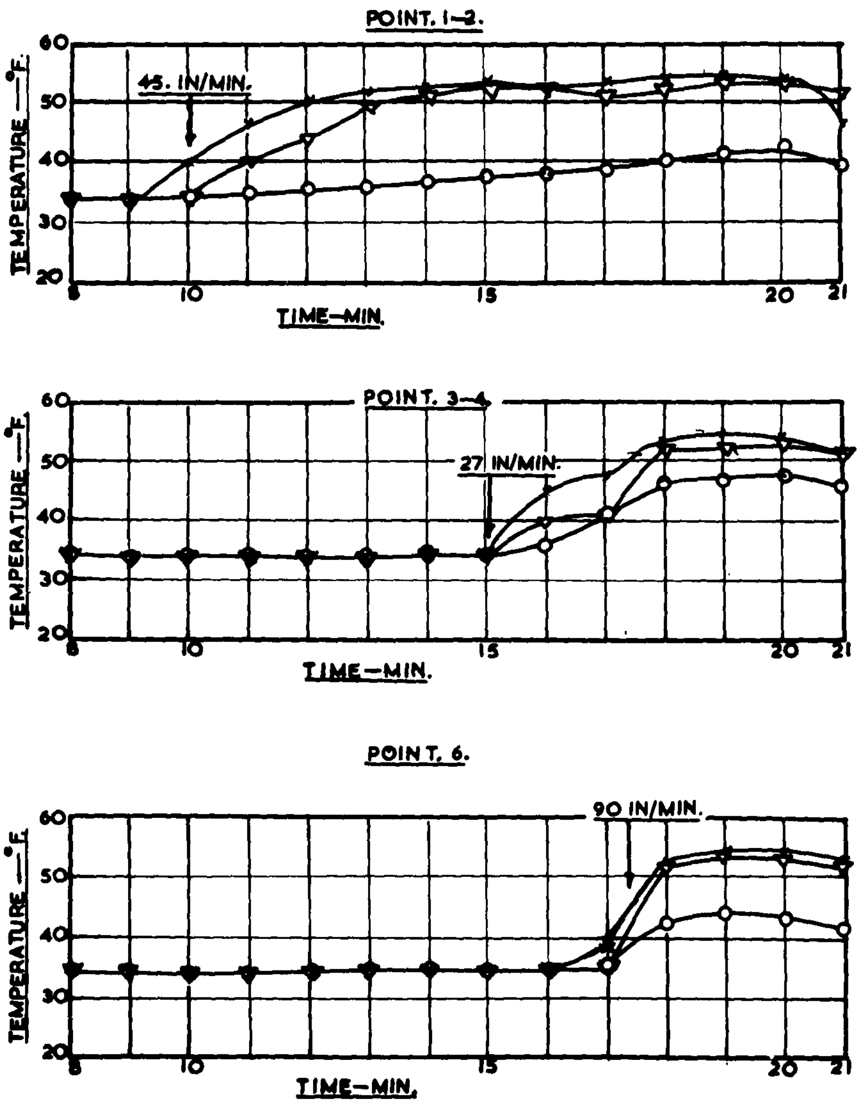


FIG. 10 FLOW RATE & SHEAR STRESSES FOR RUN 68.



o 1" FROM WALL OF PIPE AT OUTSIDE OF COIL, OR TOP OF COIL (POINT. 6).

▽ CENTRE OF PIPE.

× 1 FROM WALL OF PIPE AT INSIDE OF COIL, OR BOTTOM OF PIPE (POINT. 6)

RATE OF MOVEMENT MARKED WITH FIGURES AND ARROW.

FIG. 11. TEMPERATURE DISTRIBUTION IN PIPE IN RUN 49.

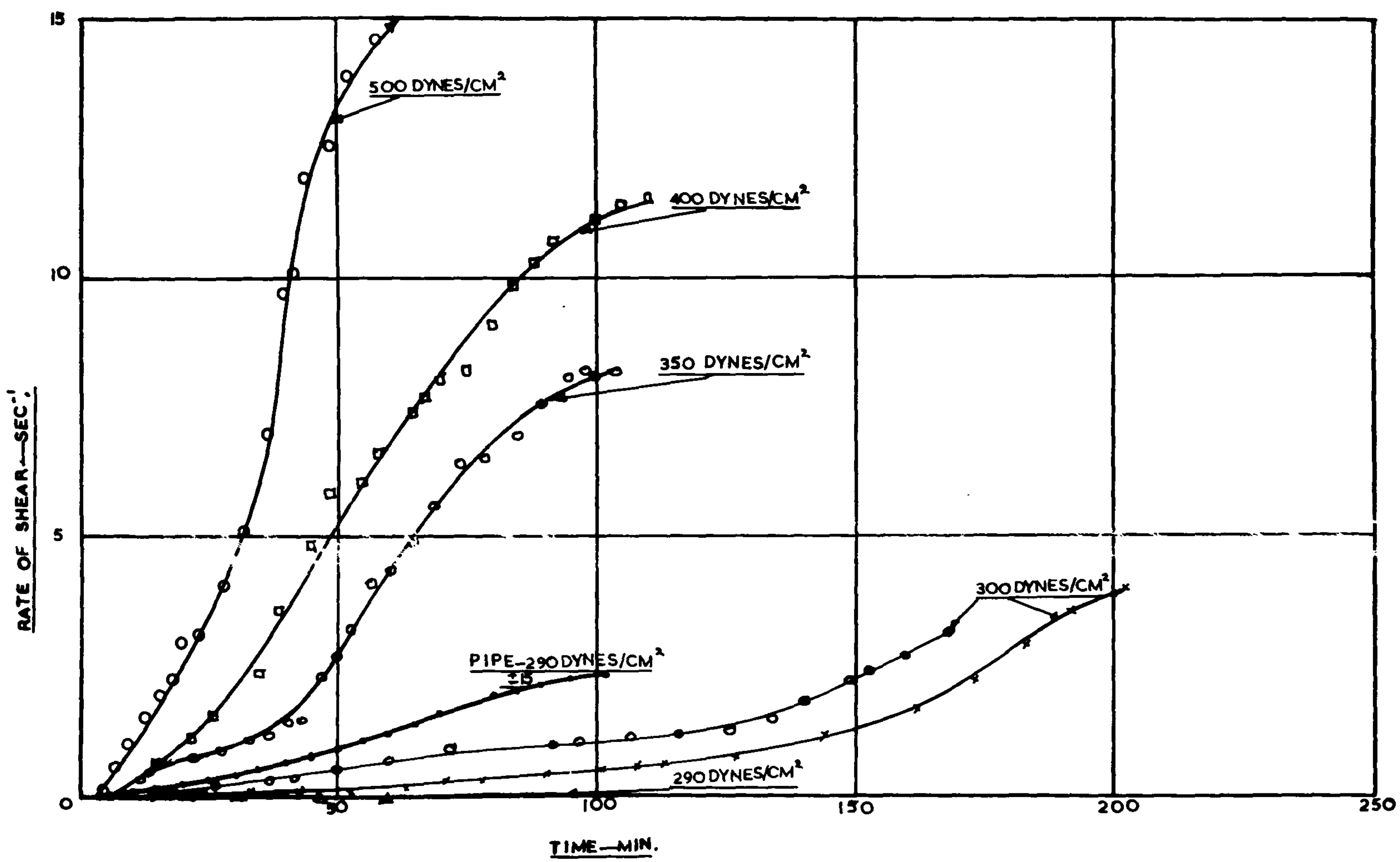


FIG.12. RATE OF SHEAR IN RUN 51 AND CONSTANT SHEAR STRESS VISCOMETERS.

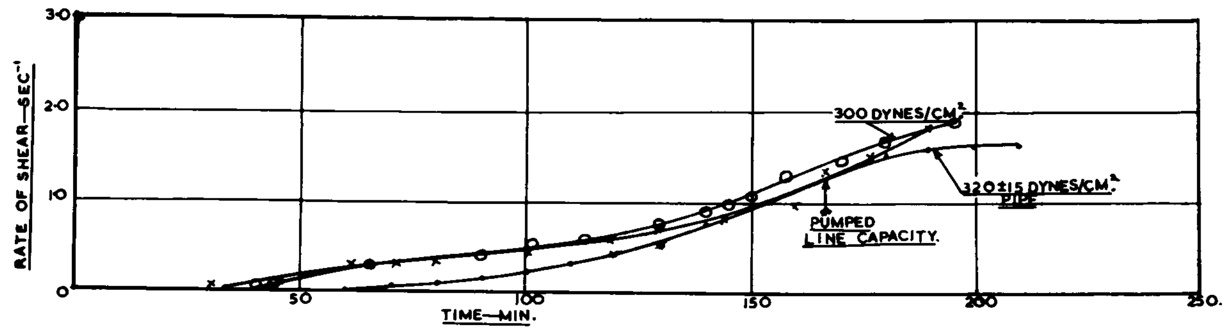


FIG. 13. RATE OF SHEAR IN RUN 57. AND CONSTANT SHEAR STRESS VISCOMETERS.

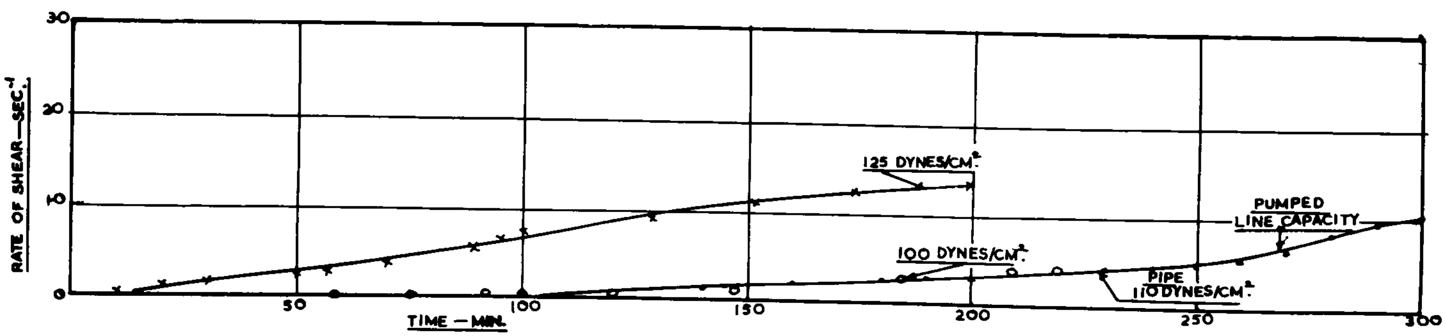


FIG. 14. RATE OF SHEAR IN RUN 62. AND CONSTANT SHEAR STRESS VISCOMETERS.

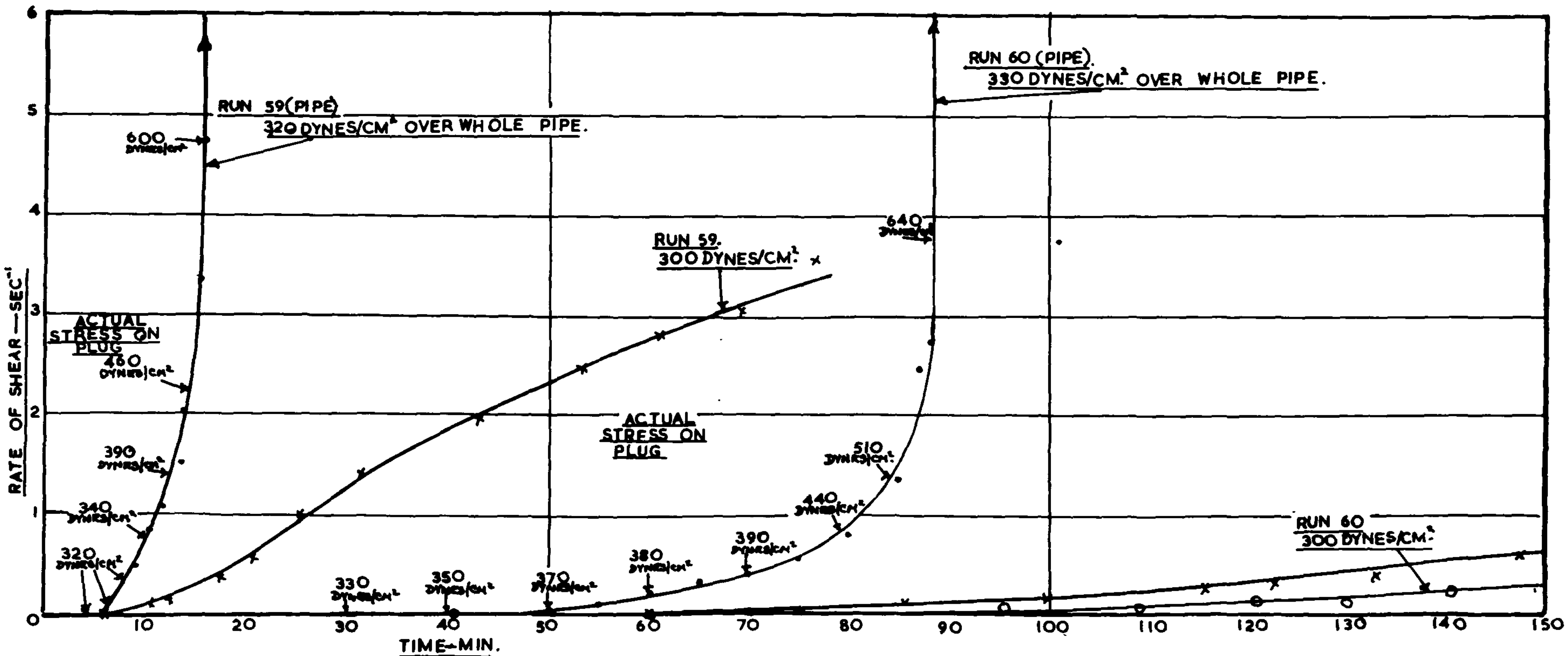


FIG. 15. RATE OF SHEAR IN LINE CLEARING RUNS 59 & 60 AND CONSTANT SHEAR STRESS VISCOMETERS.

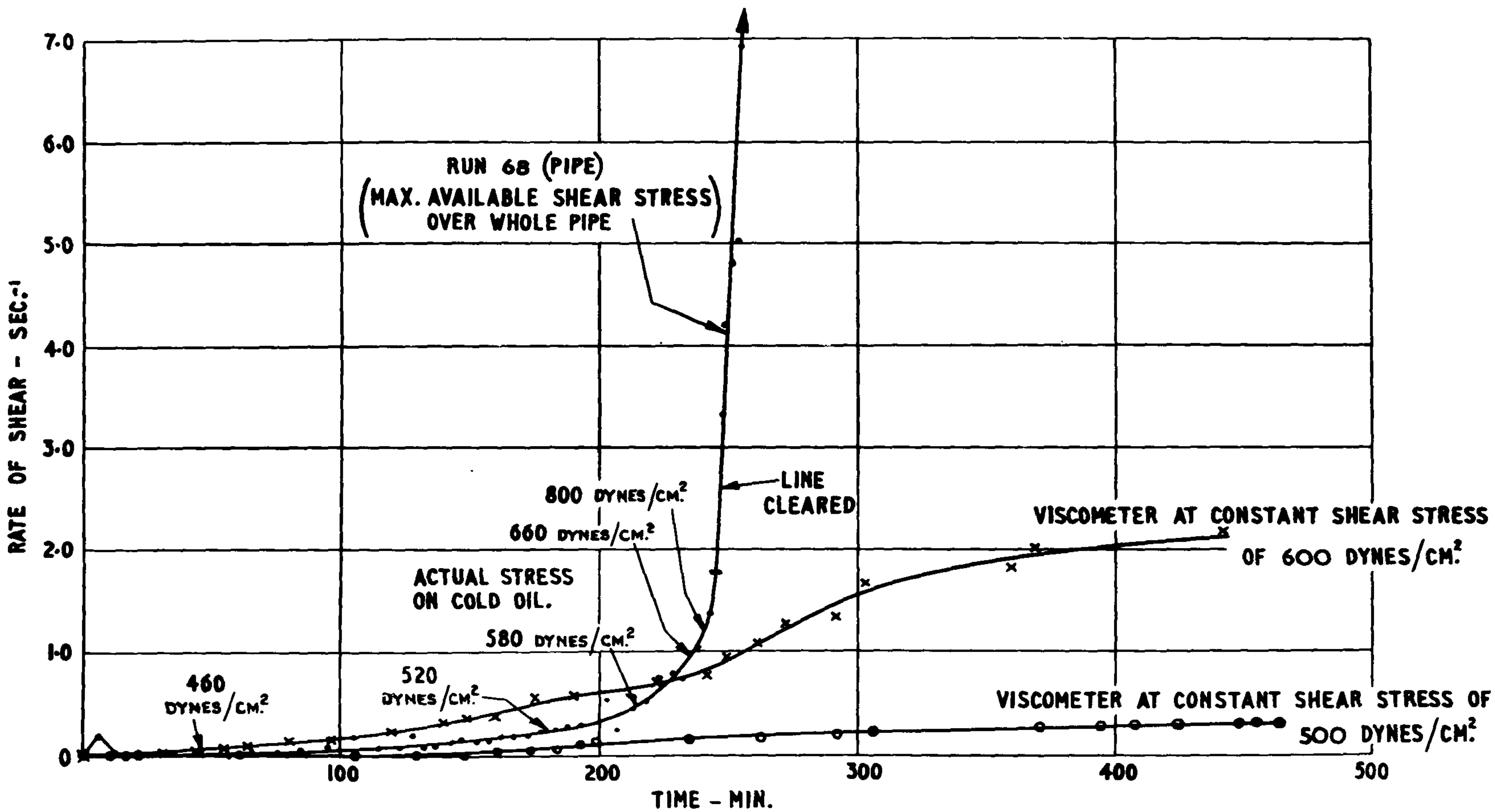


FIG. 16. RATE OF SHEAR IN LINE CLEARING RUN 68 AND CONSTANT SHEAR STRESS VISCOMETERS.

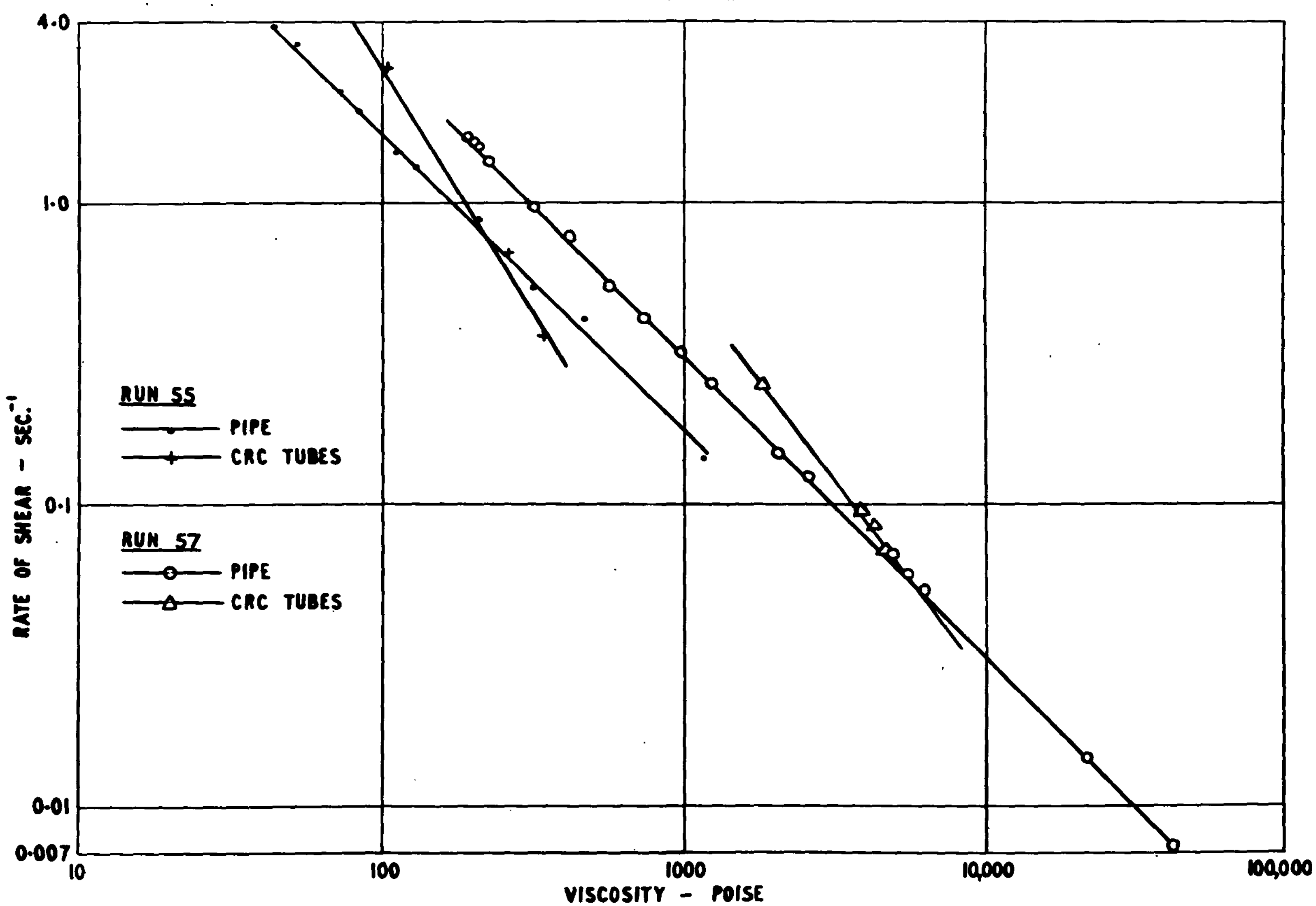


FIG. 17 TYPICAL CRC FLOW CURVES.

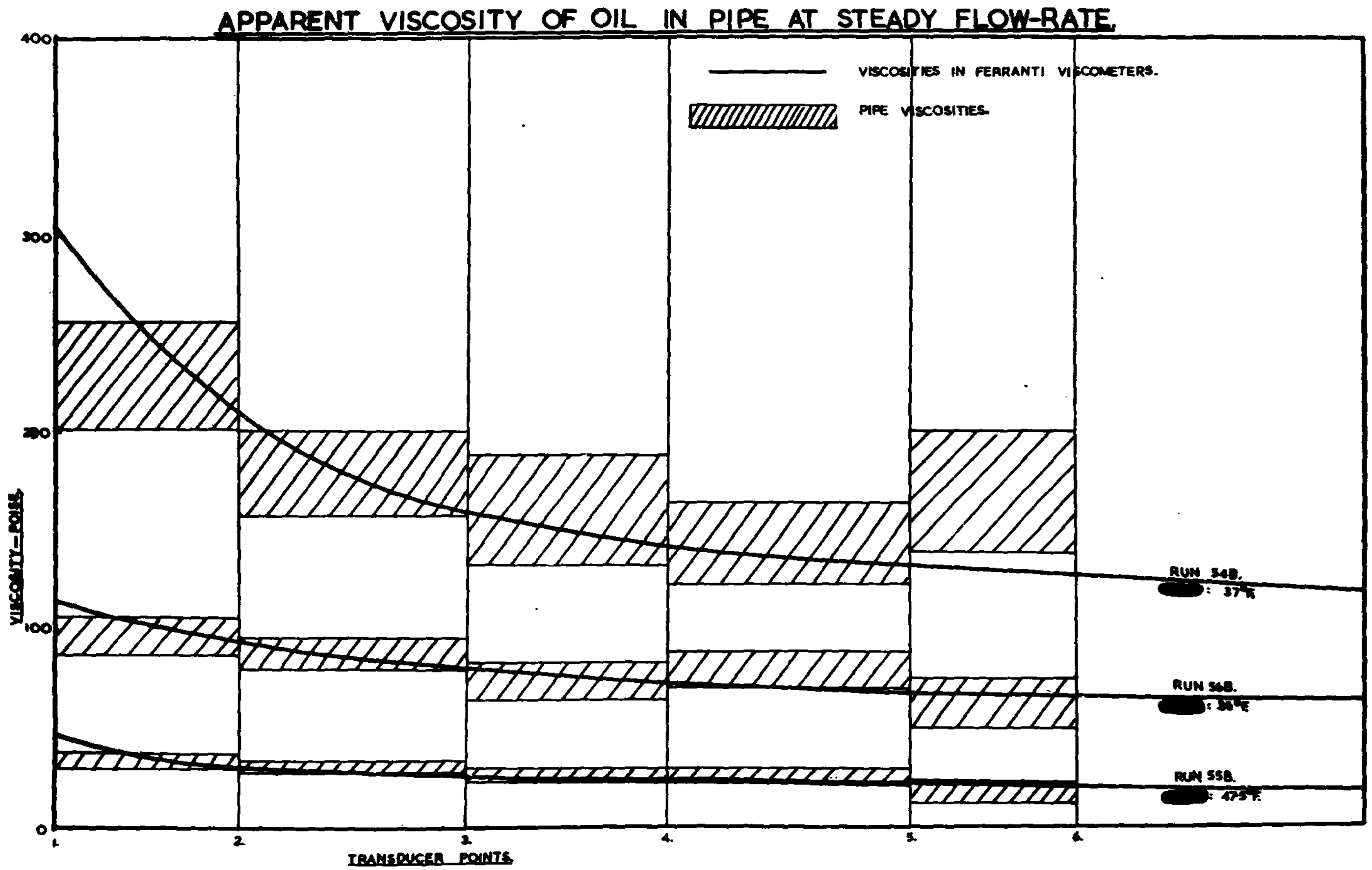


FIG. 18. VISCOSITY IN PIPE AND CONSTANT RATE OF SHEAR VISCOMETERS.

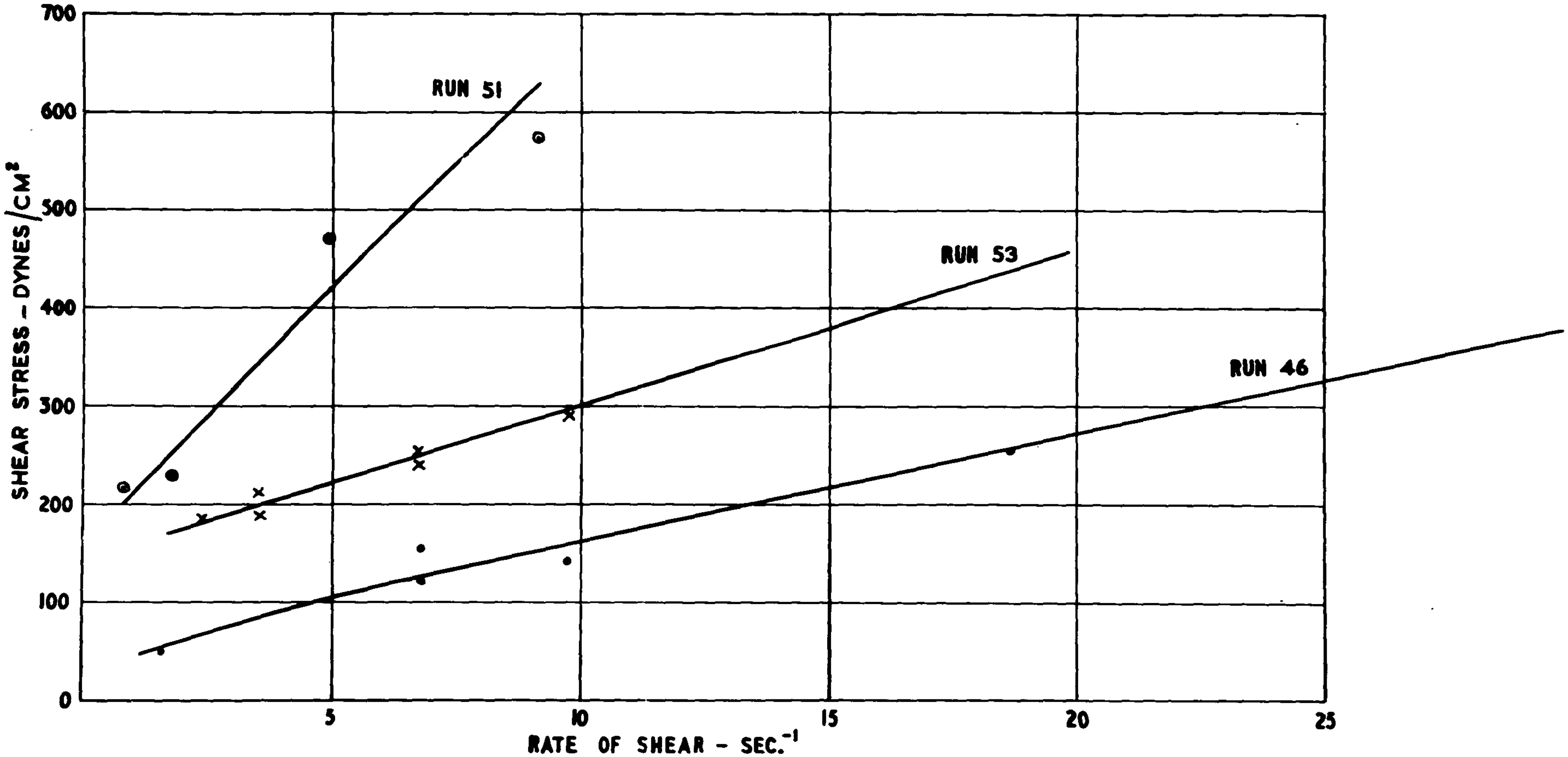


FIG. 19. RHEOGRAMS FOR PREDICTING FLOW RATES, RUNS 46, 51 & 53.

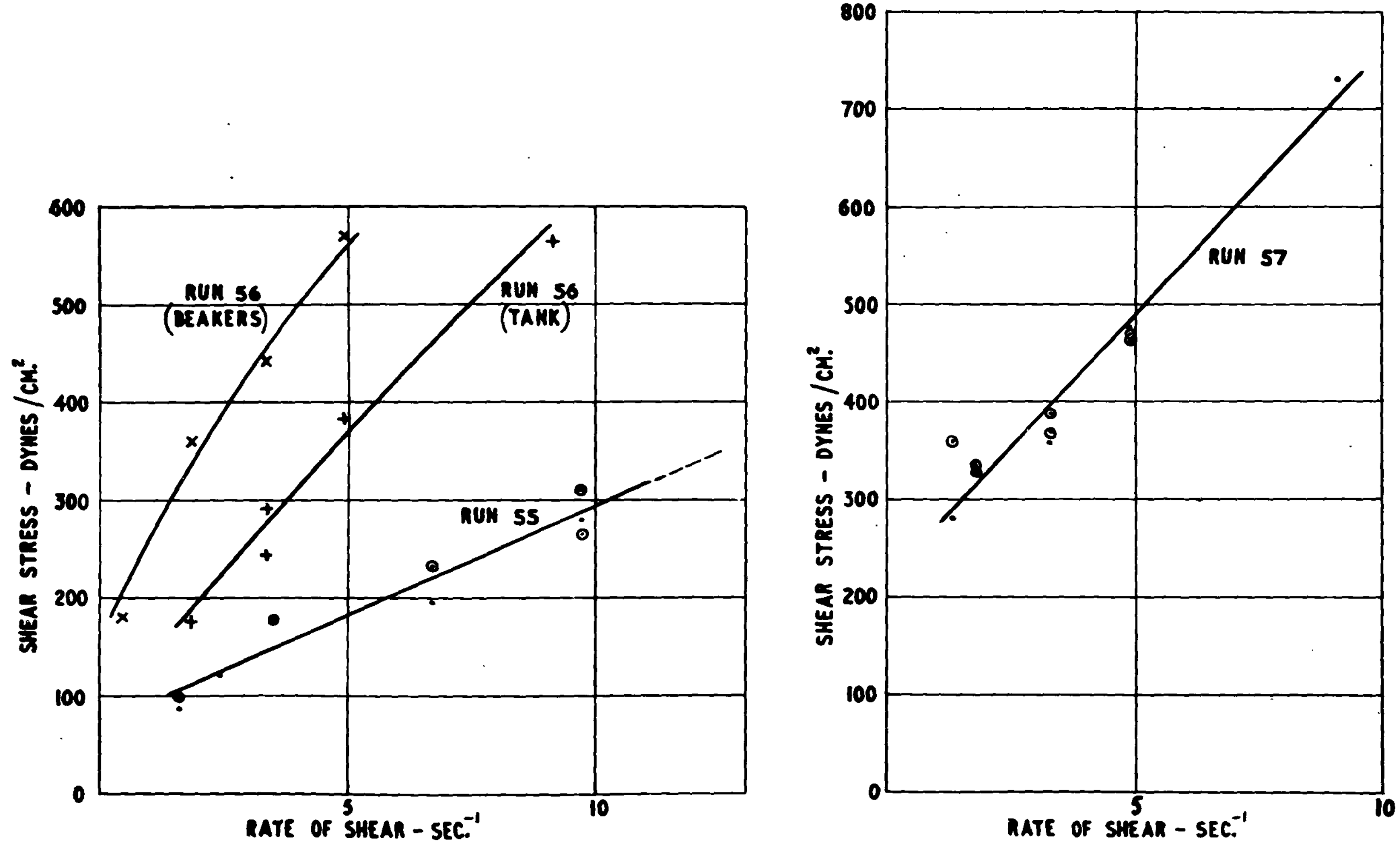


FIG. 20 RHEOGRAMS FOR PREDICTING FLOW RATES, RUNS 55, 56 & 57

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